Plenary Lecture. The history of the liquid crystal display and liquid crystal material technology

Martin Schadt[a]

[a] Central Research Units, F. Hoffmann-La Roche & Co. Ltd, Basel, Switzerland

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Plenary Lecture

The history of the liquid crystal display and liquid crystal material technology

by MARTIN SCHADT

Central Research Units, F. Hoffmann-La Roche & Co. Ltd, CH-4002 Basel, Switzerland

The milestones which have marked the development of today's liquid crystal display and liquid crystal material technologies are reviewed. The main emphasis is placed on the predominant nematic field effects and liquid crystals.

1. Introduction

Although the first observation of liquid-crystalline phenomena dates back to the 19th century, when Reinitzer attributed the optical anisotropies which he observed in molten cholesteryl benzoate to liquid-crystalline states, it was 80 years until the era of liquid crystal displays (LCDs) dawned. In the late 1960s a few industrial research groups in the U.S.A. and in Europe became interested in the strongly anisotropic material properties of liquid crystals, which at the time seemed to be rather exotic organic compounds. Attempts were made to understand better the fascinating liquid-crystalline properties and to use this knowledge to search for practical electro-optical effects and for suitable liquid crystal materials to produce electrically tunable, flat, optical shutters.

In 1968 Heilmeier et al. [1] first used the dynamic scattering effect in an electro-optical liquid crystal device. Dynamic scattering has been known since the work of Björnstahl [2] in 1918 and from further investigations by Williams in 1963 [3]. Dynamic light scattering occurs in thin layers of negative dielectric anisotropic liquid crystals upon passing an ionic current through the layers. It was the basis for the first LCDs in electronic wrist watches. However, a technical application of the dynamic scattering effect in displays was not practicable at the time of its introduction, because no suitable room temperature nematic liquid crystals were available. This changed in 1969 when Kelker and Scheuerle [4] as well as researchers at Minnesota Mining [5] discovered MBBA (4-methoxybenzylidene-4'-n-butylaniline), with its negative dielectric anisotropy which allowed the development of mixtures for dynamic scattering LCDs with practical temperature ranges.

Besides dynamic scattering LCDs, two other electro-optical effects with potential display application were discovered in the late 1960s: a nematic guest–host effect by Heilmeier and Zanoni [6] and a field-induced cholesteric–nematic phase change effect by Wysocki et al. [7]. Both are field effects; that is, the generation of the optical signal does not require an ohmic current to flow, only an electric field is required to realign a liquid crystal layer with a positive dielectric anisotropy from a defined off-state configuration into a different field-aligned on-state. In the case of the guest–host effect the optical signal is generated by dichroic dye molecules (guests) which are dissolved

in a parallel aligned (off-state) nematic host. Upon application of the field, homeotropic alignment of the host and the guests results; the selective absorption of the guest–host layer decreases. The phase-change effect is based on the change of light scattering of a low pitch cholesteric layer (off-state) [8] into an optically uniaxial, transparent on-state upon application of a sufficiently large voltage.

The discovery of these effects gave the impetus for a wider interest in liquid crystals by demonstrating their potential technological applicability. However, besides the competition from the rapidly developing and already established solid state devices, such as light-emitting diodes, the dynamic scattering effect as well as the guest–host and the phase-change effects had a number of basic drawbacks. Thus, the voltage and power requirements of dynamic scattering liquid crystal displays (DS-LCDs) were rather high. Moreover, DS-LCDs exhibit poor viewing properties as well as a sluggish appearance of their optical signal versus applied voltage. This does not render them applicable for high information content applications which require multiplexability. The poor multiplexability of DS-LCDs also applies to guest–host LCDs. Moreover, it took many more years to find and to develop relatively stable and quickly responding dichroic dyes and hosts with positive dielectric anisotropy and sufficiently large contrast ratios. In the case of the phase-change effect it was mainly the poor contrast and the lack of multiplexability which prevented its further use.

Here the dawning and the development of today's LCD and liquid crystal material technologies since the early 1970s are reviewed. From a commercial viewpoint both are virtually exclusively nematic technologies. They started in 1970 when Schadt and Helfrich [9] and later Fergason [10] filed patents on an electro-optical field effect which has become known as the twisted nematic (TN) effect [9]. A thorough review of the enormous amount of literature accumulated since the 1970s would go far beyond the scope of this review. Only the milestones which led to today's liquid crystal technology are reviewed. I apologize for unavoidable omissions, but I trust that the inspiring interdisciplinary and international collaboration between physicists, organic chemists, and electronics and display engineers which founded and further advanced today's liquid crystal technology will become visible.

2.   The twisted nematic effect

Before the unique properties of liquid crystals can be visualized in displays, electro-optical effects and suitable liquid crystal materials must be found. The operating principle of an applicable electro-optical effect has to be such that the optical appearance of a display based on the effect changes reversibly upon applying an external voltage. The contrast between the off- and the on-state should be large, as should the viewing range. Moreover, the displays have to be competitive with alternative technologies, as for instance with light emitting diodes (LEDs), vacuum fluorescent displays (VFDs) or even with the high information content television cathode ray tubes (CRTs). Therefore, the effect has to offer technological advantages such as full colour reproducibility, low power consumption, large design flexibility, compatibility with low voltage and low power integrated driving circuits, flat design, reliability, sufficiently fast response and the potential to be applicable in high information content displays such as in computer or television screens. Its advantages have to outweigh the inherent drawbacks. Moreover, the liquid crystal material parameters which the effect requires must be such that it is possible to design appropriate liquid crystal structures with properties that do not limit its potential.
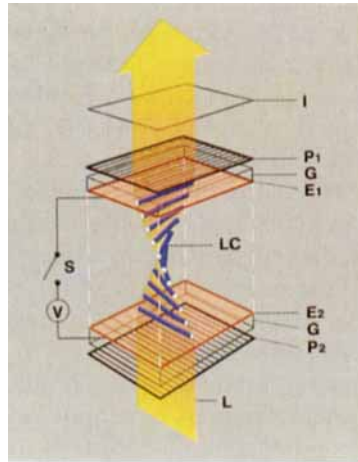
Figure 1.   Off-state configuration of a positive contrast twisted nematic liquid crystal display (TN-LCD) [9]. The wall alignment of the liquid crystal director which enforces the 90° twist is either achieved by angular evaporation of SiO_x or by coating the transparent electrodes E1 and E2 on the glass substrates with polymer layers which are brushed parallel to the respective polarizer directions of the adjacent polarizers P1 and P2. Because of waveguiding of the nematic helix, the crossed-polarizer twisted nematic configuration is transparent (image plane I white). Upon switching S on, the voltage V deforms the positive dielectric anisotropic helix parallel to the electric field such that waveguiding ceases. The nematic layer becomes optically uniaxial and the TN-LCD blocks light in the on-state. A negative contrast TN-LCD results if the two polarizers are aligned parallel.

The TN effect [9] which is predominantly used in today's LCDs has proved to be suitable for realizing most of these requirements. Since no ionic current is required to generate an optical signal with the TN configuration (see figure 1). displays based on the TN effect exhibit an extremely low power consumption of a few microwatts per square centimetre. This aspect as well as several other favourable properties have, in principle, made the TN effect an interesting candidate for display applications. A detailed review is given in [11]. However, in the early 1970s no liquid crystals were available with suitable physical properties which would have allowed TN-LCDs to operate at room temperature. Besides, TN-LCDs require two polarizers which reduce their off-state brightness by 50 per cent. Moreover, they require surface alignment of the liquid crystal molecules at the display boundaries. Thus, the TN principle was rather complicated compared with dynamic scattering LCDs. Moreover, it was uncertain as to whether the boundary alignment would survive extensive lifetime tests. Last, but not least, most solid state physicists were rather sceptical about the use of any operational organic materials in electronic devices. It was mainly the Japanese watch and electronics industry which accepted the challenge and the risks to start the new technology on an industrial basis by developing adequate production facilities for TN-LCDs. A decision which proved to be very far-sighted and successful, considering the 900 million TN-LCDs that were manufactured worldwide in 1987.

Depending on their application, TN-LCDs are operated with different optical path differences $\Delta n \, d$ which require different liquid crystal materials and cell gaps. Maximum contrast results when [14]

$$\Delta n \, d / 2\lambda \;=\; 0.5, \, 1, \, 1.5, \ldots , \tag{1}$$

where d is the cell gap. $\Delta n = (n_e - n_0)$ is the optical anisotropy and λ is the wavelength of light. Under these maximum contrast conditions virtually no elliptically polarized light is generated in the helix of figure 1. Therefore, the light dispersion is small in this 'wave-guiding' mode [9] which was treated mathematically by Berreman [15]. As a consequence, properly designed TN-LCDs exhibit large contrast ratios which are limited only by the polarizers. Moreover, TN-LCDs appear black–white with grey levels at intermediate driving voltages. Their black–white appearance allows them to be combined with colour filters such that the full range of colours of the visible spectrum can be reproduced by mixing the three basic colours yellow, red and blue. To avoid reverse twist and reverse tilt domains in $\varphi = 90°$ twisted TN-LCDs (see figure 1), special polymer boundary aligning configurations [17] and the use of long pitch cholesteric dopants [16] were developed.

The polymer surface aligning techniques [13, 17] and the polymer sealing techniques which Japanese LCD manufacturers developed in the mid-1970s proved to be much more suitable for mass-production of TN-LCDs than angular evaporation of SiO_x [12] and glass-frit sealing. The polymer processes allowed the change from high temperature glass-frit sealing to low temperature processes.

So far the most sophisticated application of TN-LCDs is in actively addressed thin film transistor (TFT) TN-LCDs [18, 19] for flat colour television screens and for very high information content graphics displays with more than one million picture elements for aeroplane cockpits [20].

3. LCD-addressing: time multiplexing, active addressing and dual-frequency
3.1. Time multiplexing

The complexity of TN-LCDs has been impressively increased since their first application in simple $3\frac{1}{2}$ digital watch displays in 1972 [21] and in pocket calculators in the mid-1970s. Currently available (figure 2), passively addressed dot matrix TN-LCDs comprise up to about 100 000 picture elements (pixels). To address each pixel of such a medium complex display via individual connections would be technologically impossible. Therefore, time multiplexed addressing techniques were
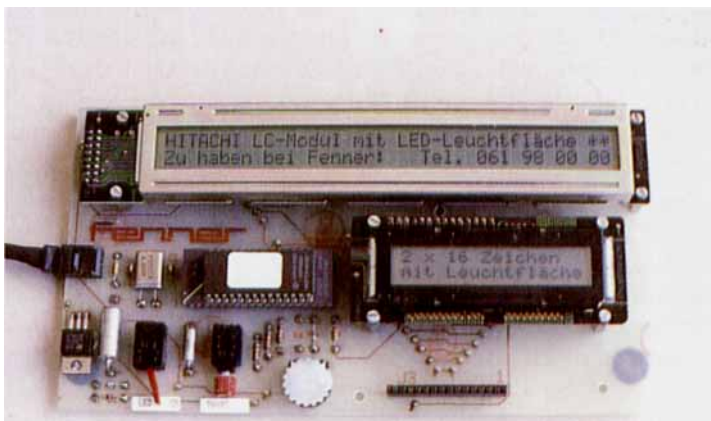

Figure 2.   Two different TN-LCD modules with drivers.

developed [23–25] which make use of the specific electro-optical characteristics of the LCD to reduce drastically the number of connections of a matrix of N lines and M columns from $(N \times M)$ to $(N + M)$. A review on addressing techniques was recently published by Kaneko *et al.* [25]. Prerequisites for multiplexing operation are a well-defined optical threshold and a steep transmission–voltage characteristic of the electro-optical effect. The principle of multiplexing is shown in figure 3. We shall see later that to take full advantage of the potential steepness of the characteristics of a given electro-optical effect, liquid crystals with specifically designed material properties are required [11].
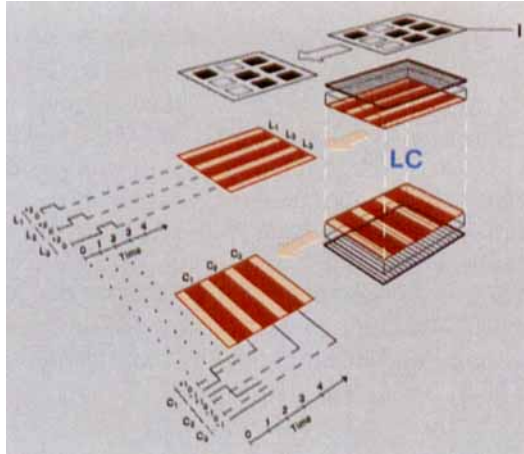

Figure 3. Principle of time multiplexing the lines L_i and columns C_i of a TN-LCD. The optical threshold is assumed to be $V_0 < 1$ = non-select voltage, whereas the effect is fully developed at the select voltage $V = 3$. From the superposition of the line and column addressing signals follows the image I.

According to Alt and Pleshko [22] the maximum number, N, of multiplexible lines is given by

$$\frac{[(1 + p)^2 + 1]^2}{[(1 + p)^2 - 1]}, \quad p = \frac{(V_{50} - V_{10})}{V_{10}}, \tag{2}$$

where the slope parameter p in equation (2) is defined such that a contrast of $5:1$ results. V_{50} is the voltage for 50 per cent transmission of the LCD, whereas V_{10} corresponds to 10 per cent transmission. It follows from equation (2) that the LCD contrast decreases (below $5:1$) if N is increased beyond a minimally required value p_{min}. p_{min} is determined by the inherent steepness of the electro-optical effect used in the LCD and by the liquid crystal material parameters governing the effect. Moreover, with increasing N the electro-optical response times of the LCD increase and the range of view decreases due to the reduction of contrast. We shall see later that the limitations of time-multiplexing of TN-LCDs can be overcome not only by actively addressing TN-LCDs, but also with supertwist configurations which exhibit much steeper characteristics. However, if, as in television applications, fast response *and* high contrast *and* wide viewing range *and* a large number of grey levels have to be achieved, actively addressed TN-LCDs which comprise an integrated solid state driver in each pixel appear, although technologically highly demanding, to be the best choice.

3.2. *Active LCD-drivers*

Devices for actively addressing LCDs are metal–insultor–metal (MIM) diodes [26] varistors [27], metal–oxide–substrate (MOS) transistors [28] and TFTs [18, 19]. For a review of active addressing techniques see [23]. Among them TFT televisions, which were pioneered by Seiko Epson and Hitachi, receive the greatest attention. Recently the first pocket colour television sets with up to 5 inch (12·7 cm) diagonal TFT-TN-LCDs were commercialized by Hitachi, Matsushita and Sharp. To achieve a broad range of view [29] low birefringence liquid crystal materials which allow the TN-LCD to operate in its first minimum (see equation (1)) are required for TFT-addressing.

3.3. *Response times of nematic and ferroelectric LCDs*

To improve the turn-off times of LCDs, especially in optical shutter applications where response times below 1 ms are required, dual frequency addressing can be applied [30]. This addressing technique is based on the reversal of the sign of the dielectric anisotropy $\Delta\varepsilon = (\varepsilon_\parallel - \varepsilon_\perp)$ of liquid crystals with positive dielectric anisotropy at high frequencies due to the hindered rotation of the long molecular axes [31–33]. At room temperature, where the dielectric dispersion of normal nematics lies above 100 kHz, specially designed mixtures are required to lower the dielectric crossover frequency f_c [$\varepsilon_\parallel(f_c) = \varepsilon_\perp$] into the 10 kHz range. At low frequencies dielectric heating does not occur [34] and the capacitive load on the drivers does not become too heavy. Figure 4 shows the shortening of the turn-off time of a dual frequency addressed TN-LCD [32].
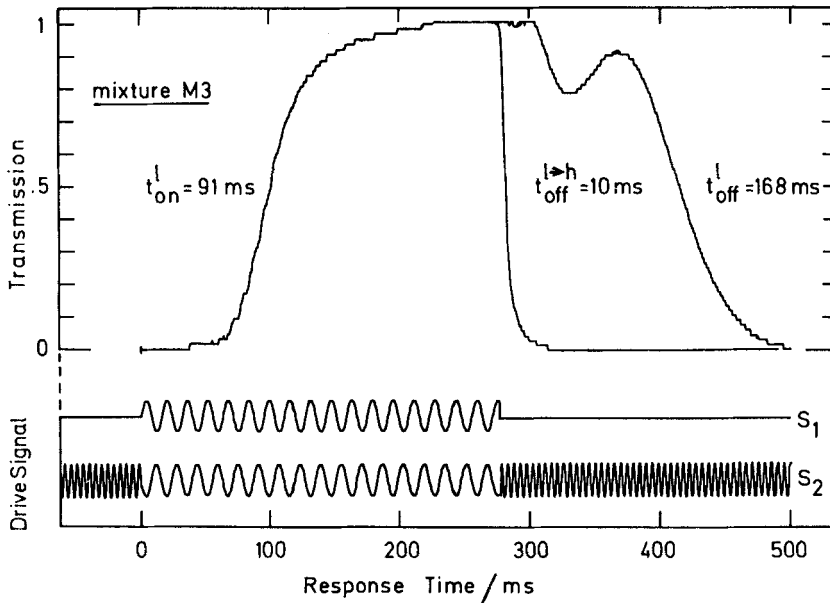

Figure 4.   Shortening of the turn-off time of a dual frequency addressed TN-LCD [32].

Until recently the dual frequency approach seemed to be the only way, besides the fast-switching π-cell [36], to achieve millisecond response times at room temperature with LCDs driven at moderately low voltages. However, the discovery of ferro-electricity in liquid crystals by Meyer *et al.* in 1975 [37] which was followed in 1980

by the discovery of the surface stabilized ferroelectric (SSF) effect by Clark and Lagerwall [38] made response times in the microsecond region possible with liquid crystals [39]. Thus, despite some still pending technical problems, the response times of SSF-LCDs are orders of magnitude faster than those of nematics. Moreover, SSF-LCDs do not suffer from the strong temperature dependence of the crossover frequency of dual frequency addressable nematics [32].

4. Liquid crystal material parameters

The unique anisotropic optical, electrical, magnetic and mechanical material properties of liquid crystals, which are detailed by de Gennes [40] and by Chandrasekhar [41], are fundamental for their applications in displays. They result from molecular specific electronic and steric anisotropies, combined with short and long range intermolecular interactions [42–44]. Figure 5 shows an example of three possible equilibrium configurations of a $1d_3CP$ cyanophenylcyclohexane alkenyl liquid crystal molecule [45] whose rod-shape has been obtained from interactive molecular graphics modelling [46].
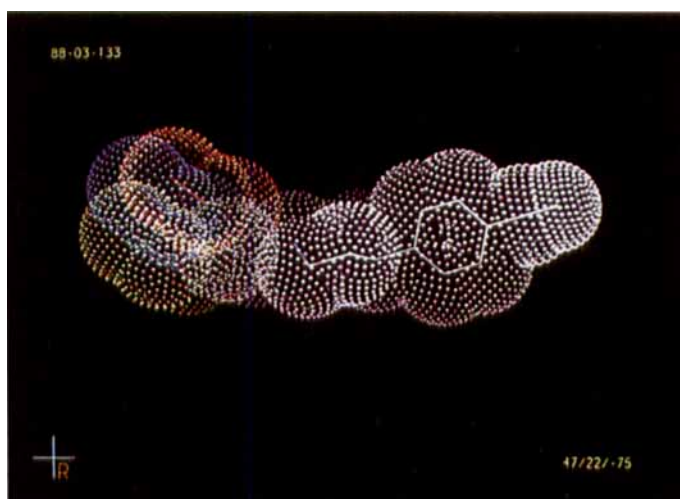
Figure 5.   Three possible configurations of the alkenyl side chain (yellow, blue, red) of a $1d_3CP$ cyanophenylcyclohexane liquid crystal molecule [45]. The dots show the van der Waals radii.

Since the material properties of liquid crystals are the result of their molecular properties amplified by the long range intermolecular order of the liquid-crystalline state, the proper design of liquid crystals for each specific electro-optical effect and its many applications is crucial. Moreover, reliable experimental techniques are required to determine the material parameters which can then be related to the performance of the liquid crystal in a display.

The rather elaborate techniques required to determine the splay (k_{11}) and bend (k_{33}) elastic constants as well as a method to determine the twist constant (k_{22}) in the same experiment reliably are reviewed in [47]. Experimental techniques to determine the static and dynamic dielectric constants $\varepsilon_\perp$, $\varepsilon_\parallel$ and the conductivities $\sigma_\perp$, $\sigma_\parallel$ via the complex, frequency dependent impedance of oriented liquid crystal layers are described in [31, 32, 48]. Optical techniques to measure the viscosity coefficients

η_i can be found in [49, 50], whereas [51, 52] describe methods to determine the rotational viscosity γ_1 which is the most important viscosity for display applications [53].

It was only in the early 1980s that the experimental techniques, especially those to measure elastic constants reliably, were developed and could be used to find correlations between all of the relevant material parameters of nematic liquid crystals and their influence on the electro-optical performance of LCDs. For TN-LCDs and a number of different liquid crystal classes this was first done by Schadt and Gerber [53, 54], who also derived analytical approximations to illustrate the complex relationships between material parameters and the multiplexability of TN-LCDs. Except for the rotational viscosities γ_1 and for the twist elastic constants k_{22}, Scheuble et al. [55] investigated at about the same time the material properties of mixtures comprising cyanophenylcyclohexanes [56]. Investigations made before 1980 usually excluded important material parameters [57] or used methods, especially to determine the elastic constants, which did not provide reliable data. Therefore, and because of the lack of electro-optical investigations with class-specific liquid crystals, reliable correlations between liquid crystal material properties and molecular structural elements have become possible only within this decade.

The following approximations illustrate some of the relationships between these material parameters and the electro-optical performance of TN-LCDs [9, 54], super-twist nematic (STN) LCDs [58, 59] and optical mode interference (OMI) LCDs [60]. In addition, correlations between molecular structural elements and liquid crystal material parameters can be found in the same articles.

$$V_{10}(\text{TN-LCD}) \propto \pi \left(\frac{k_1 + (k_3 - 2k_2)/4}{\varepsilon_0 \Delta \varepsilon} \right)^{1/2}, \quad [9, 54] \qquad (3)$$

$$t_{\text{off}}(\text{TN-LCD}) \propto \gamma_1/\kappa, \quad [45, 61] \qquad (4)$$

$$p(\text{TN-LCD}) \propto (k_{33}/k_{11} - 1) + \left(\ln \frac{\Delta n \, d}{2\lambda} \right)^2, \quad [54] \qquad (5)$$

$$p(\text{STN-LCD, OMI-LCD}) \propto k_{11}/k_{33}; \; \Delta \varepsilon/\varepsilon_\perp; \; k_{22}/k_{11}. \quad [59, 60] \qquad (6)$$

Here p is the slope parameter (see equation (2)), t_{off} is the turn-off time of a TN-LCD and κ is the elastic expression which occurs in the denominator of equation (3) [45, 61].

5. Material requirements of electro-optical effects

The few approximations given in equation (3)–(6) show that combinations of different, often conflicting, dielectric, optical, elastic, viscous and thermal material properties are required to achieve a good overall performance of an LCD. The requirements are different for different electro-optical effects as well as for different LCD applications. Thus, essential prerequisites for outdoor LCDs are materials with wide operating temperatures which still lead to short response times at $-30°C$, whereas high information content LCDs for computer applications require materials which are either TFT-compatible or highly multiplexable, depending on the addressing scheme and on the electro-optical effect used. For electrically tunable retardation effects [62–67], materials with positive or negative dielectric anisotropies and large birefringences are needed primarily. Whereas the opposite often holds for hosts of quest–host LCDs [6, 68–70]. For the fast-responding (nanoseconds) but rather exotic Kerr effect in the isotropic phase of liquid crystals [71], positive dielectric and

optically strongly anisotropic, two-ring structures lead to Kerr constants which exceed those of standard Kerr fluids by a factor of 200. Reversible optical storage effects can be achieved by doping nematic mixtures with cholesteric additives such that short pitch cholesteric focal conic textures result which strongly scatter light in the off-state [72–74]. Bistable electrical switching between two transparent, cholesteric 'supertwist' configurations [75] requires long pitch cholesteric additives for nematic mixtures. High resolution thermally induced optical storage can be achieved in smectic A layers with laser scanning [76, 77] as well as with resistor heating [78]. In addition to ferroelectric chiral smectic C layers [38, 39], short response times can be achieved with electroclinic effects in chiral smectic A layers [79].

Each homologous series (class) of liquid crystals and still more so each single liquid crystal component exhibits only a few outstanding material properties. To achieve nevertheless a good overall LCD performance within the range of the best liquid crystal components known at a given time, complex mixtures comprising up to 20 components have to be designed. This allows the optimization of more than ten different material parameters which determine, for instance, the performance of TN-LCDs [54].

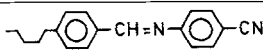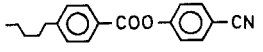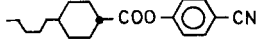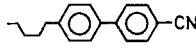## 6. Structures of liquid crystals
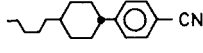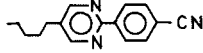
The development of the LCD technology is closely related to the progress made in liquid crystal materials since the early 1970s. Modern liquid crystal mixtures comprise molecules which belong to different liquid crystal classes. Each class consists of structurally similar molecules exhibiting class-specific physical properties [54, 55]. Summaries of the thermal data of virtually all liquid crystal classes published until 1981 can be found in the tables prepared by Demus and co-workers [80, 81].

The following table depicts a few two-ring representatives of technologically important nematic liquid crystal classes. All of them essentially contributed to the development of today's LCD technology. From them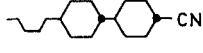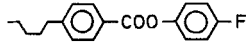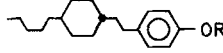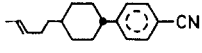 a large number of spin-offs of similarly important polar and non-polar two-, three- and four-ring structures resulted. Their performance justified manufacturing on a large scale.

The cyano-Schiff's bases at the head of the table were the first positive dielectric anisotropic nematics that were developed, by Boller *et al.* [21], to support the commercialization of TN-LCDs after the TN effect was discovered in 1970 [9]. They possessed a sufficiently wide nematic range and sufficiently low operating voltages to be applicable in commercial TN-LCDs [21]. However, due to the hydrolysis of the Schiff's base linkage in contact with humidity, Schiff's bases could no longer be used in the polymer-sealed TN-LCDs whose production started in the mid-1970s in Japan. For plastic sealed TN-LCDs, the cyano-biphenyls, which were discovered by Gray *et al.* in 1974 [82], and to a lesser extent also the cyano esters [83, 84], proved to be much more compatible. Therefore, and because of the low viscosities of cyano biphenyls, they became very successful in subsequent low and medium multiplexable TN-LCDs for watches and calculators. The large optical anisotropy Δn of biphenyls also renders them suitable for electrically tunable birefringence effects such as in the projection light-valve described by Margerum and co-workers [66, 85].

Another important structure was reported by Demus *et al.* [84] in 1973 which showed that nematic phases cannot be achieved only with molecules like Schiff's bases or biphenyls which comprise exclusively aromatic phenylrings in their rigid cores (see the table). The phenylcyclohexane esters were the first nematic liquid crystals comprising one cyclohexane ring, with its weak optical anisotropy, in their core (see the table).

Two-ring representatives of technologically important nematic liquid crystals.

Year	Structure	Ref.
1971	~/○-CH=N-○-CN	[21]
1972	~/○-COO-○-CN	[83]
1973	~/⬡-COO-○-CN	[84]
1974	~/○-○-CN	[82]
1977	~/⬡-○-CN	[86]
1977	~/○-○-CN	[87]
1978	~/⬡-⬡-CN	[88]
1981	~/○-COO-○-F	[89]
1983	~/⬡-○-OR	[90,91]
1985	~/⬡-○-CN	[45]

With increasing sophistication of the TN-LCD technology the liquid-crystal material requirements, especially towards shorter response times, wider nematic ranges, lower operating voltages, multiplexibility, etc., became increasingly demanding; a trend which will continue as long as the large potential of the technology is not been exhausted. Thus, another important improvement, especially towards shorter response, wider mesomorphic temperature ranges and further improved thermal and light stability was the discovery of the cyanophenylcyclohexanes (PCHs) by Eidenschink et al. [86] in 1977 (see the table). With PCHs it became possible to develop, for the first time, wide temperature range mixtures for automotive applications with sufficiently short response times at −30°C, At about the same time the first heterocyclic polar nematics were developed by Boller et al. [87] (see the table) which contributed strongly to increasing the number of multiplexable lines of TN-LCDs [54].

In 1978 the cyanobicyclohexanes were found by Eidenschink et al. [88] (see the table), which proved that even non-aromatic rigid cores can lead to nematic phases. These low birefringence materials made operation of TN-LCDs possible in their first transmission minimum (see equation (1): $\Delta n \, d/2\lambda = 0.5$), where wide viewing angles result [29]. Further advances towards even shorter response times were achieved with the fluorinated esters of Inukai in 1981 [89] and with the non-polar ethanes described by Schadt et al. [90] and by Takatsu et al. [91]. However, neither these classes of liquid crystals nor combinations of them exhibit all of the desired broad range of properties.

Indeed, if fast response and/or high information content supertwist conformations are to be achieved, elastic constants are required which can be tuned over a broad range without deteriorating other properties. Thus, to push the technological limits further, new and more sophisticated liquid crystal materials are required. Recent examples for this development are the alkenyls which were found by Schadt and co-workers [11, 45, 92] (see the table), who showed that the introduction of double bonds into specific side chain positions leads to strong odd–even effects in the material properties of liquid crystals. As a consequence, especially the bandwidth of elastic properties was considerably expanded.

7. Highly multiplexable supertwist effects

Because of the limited multiplexability of TN-LCDs to about 100 lines and due to the complexity of actively addressed TN-LCDs, highly multiplexable electro-optical effects remain of strong interest for all those many applications which do not require short response times and grey scales, such as television screens.

Recently, several groups have discovered electro-optical supertwist configurations with remarkably steep characteristics. Those effects are the bistable, 360° cholesteric effect by Berreman and Heffner [75], the bistable guest–host effect by Waters *et al.* [93], the superbirefringence twisted effect (SBE) by Scheffer and Nehring [94], the STN-LCD by Kando *et al.* [95], the double layer (DL) STN-LCD by Kimura *et al.* [96] and by Watanabe *et al.* [97] and the optical mode interference (OMI) effect by Schadt and Leenhouts [60] and later by Kawasaki *et al.* [98]. Both STN- and SBE-LCDs depend strongly on the electrically tunable, large optical path difference of their respective liquid crystal configurations. Therefore, both exhibit strong interference colours; black–white images are not possible in single layer configurations. Moreover, both require a very precise cell spacing d, with gap variations around $0.1 \, \mu m$, as well as materials with high nematic–isotropic transition temperatures. Further, SBE-LCDs require large boundary tilt angles which pose technological problems.

The inherent interference colours of STN-LCDs can be overcome with DL-STN-LCDs. However, DL-STN-LCDs also require a very precise cell gap spacing, which leads to increased production costs. Conversely, OMI-LCDs whose principal
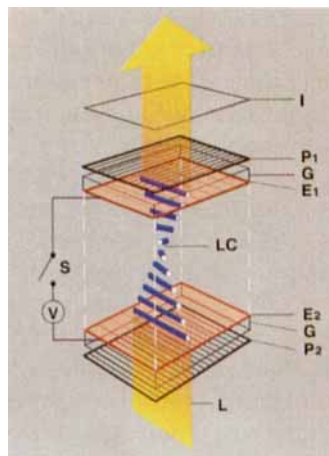

Figure 6. OMI-LCD off-state configuration [60].

Figure 7.   400 line multiplexed black–white supertwist LCD in front of a cathode ray tube terminal.

configuration is shown in figure 6 are insensitive to cell gap variations [60]. Their appearance is black–white, they can, therefore, be combined (like DL-STN-LCDs) with colour filters. Their main drawback when operated in reflection is their low off-state brightness when using small twist angles $\varphi \approx 180°$. However, this can be remedied by increasing φ to about 230°.

Which one of these effects will eventually be used on a larger scale remains to be seen. However, the possibility of combining black–white effects with colour filters gives them an advantage. Figure 7 shows a 400 line multiplexed black–white super-twist prototype.

8.   Conclusions

The rapid development since the early 1970s towards today's complex and power-ful liquid crystal technology is the result of the collaboration between scientists and engineers from different faculties, nationalities and cultural backgrounds. It is also the result of the intense interactions between research and application. Today, the rapidly expanding LCD technology has come close to one of its ultimate goals: the flat, full colour, quickly responding, large area and high information content display. This goal, which some thought to be too far fetched just a few years ago, now begins to materialize. Recently the manufacturing of actively addressed, colour, pocket tele-vision sets with 5 inch (12·7 cm) diagonal TN-LCDs was started by several Japanese companies. The realization of full-size, flat television LCD screens and large area projection LCDs for future high definition television sets seems feasible.

Apart from actively addressed TN-LCDs, much progress is being made towards highly multiplexable LCDs based on supertwist electro-optical effects and new liquid crystals. Today, high contrast, A4-size, black–white as well as colour LCDs can be realized with up to 400 multiplexed lines. They are being applied in computer terminals, as graphics displays for navigation systems in cars, in office machines, etc.

As the 12th International Liquid Crystal Conference has shown, much progress was recently made also in ferroelectric chiral smectic C liquid crystals. The possibility

of finding new solutions and new electro-optical effects to solve the pending technological problems with ferroelectrics has increased.

Never before in the short history of LCDs and liquid crystal materials has so much obvious progress been made as we see today. This makes the future of this fascinating and rapidly expanding technology look bright.

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