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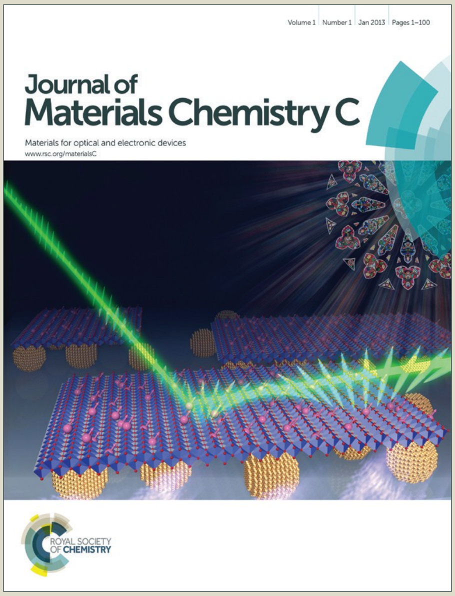

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Liquid crystals: emerging materials for use in real-time detection applications

Ding Wang, Soo-Young Park, Inn-Kyu Kang*

Department of Polymer Science and Engineering, School of Applied Chemical Engineering, Kyungpook National University, Daegu 702-701, South Korea

E-mail: ikkang@knu.ac.kr

ABSTRACT

With the rapid advances in liquid crystal (LC) materials technology over recent decades, many different practical devices have been developed and commercialized. LC devices have found numerous applications in fields such as imaging, microscopy, spectroscopy, and optical probing. Multifarious LC-based sensors have been developed to analyze label-free polyelectrolytes, ions, molecules, and biological systems. The detection principle in these LC sensors is based on the highly sensitive orientational response of LC molecules to minute changes in surface structures. Moreover, due to their potential applications in fields such as chemistry, biomedicine, and environmental science, scientists have been attracted to the research and development of LCs because of their potential use in real-time sensors. This review presents a brief overview of the historical background on the research progress of LCs and recent trends in their use in real-time detection applications.

1. Introduction

Liquid crystals (LCs) are responsive to external electric and magnetic fields, and will reposition themselves into collective alignment in the presence of an applied field. Today, LCs are well known for their applications in display technology. Liquid crystal display (LCD) technology has dominated international research efforts in display applications for quite a long time, driven by consumer demand. LCD technology is so much better today that continued research and development for day-to-day applications is conducted mainly in industrial laboratories.

LCs, which assemble with polymers and aqueous solutions, have attracted much attention in recent years because of their large surface areas and unique optical properties.[1] In bulk, LC molecules arrange themselves in arbitrary orientations. However, blended with various surfactants, polymers, and other materials, and confined by space, LC molecules are forced to assume a specific directional orientation dictated by local intermolecular forces within the aqueous phase. Due to long-range orientation correlations, the energy required to perturb the molecular order of LCs is very small.[2-4] The alignment of LC molecules is therefore very sensitive to the type, strength, and concentration of surfactants and/or polymers existing in the aqueous phase. The orientation of LCs acts as an amplifier for local perturbations caused by foreign molecules adsorbed on the interface.[5] The LCs at the surface can then communicate their orientations through the bulk, causing changes in orientations throughout the LC matrix. This process then can generate optical textures that are visible to the naked eye under crossed-polarizers in real time.[1]

2. Historical perspective

From 1850 to 1888, researchers in physics, chemistry, biology, and biomedical science found that some materials demonstrated very unusual properties near their melting points. It was observed further that the optical properties of these materials changed continuously with increasing temperatures. In 1850, W. Heintz reported that stearin melted from a solid to a cloudy liquid at 52 °C, changed to an opaque liquid at 58 °C, and then to a clear liquid at 62 °C.[6,7] In 1888, an Austrian botanical physiologist named Friedrich Reinitzer[6] observed “double melting” behavior for cholesteryl benzoate (Fig. 1a). (The chemical structure of cholesterol was still unknown. Today we know that the observed compound was cholesteryl benzoate.)

Research in the area of LCs continued to grow and expand in the years after 1888. In the beginning, every LC substance that had been identified and researched was naturally occurring. It was not until 1890 that Gatterman and Ritschke prepared the first synthetic LC, p-azoxyanisole (Fig. 1b).[7] However, between World War II and 1958, researchers thought they had learned everything possible about LCs and that there was nothing new to be explored. New young scientists did not have any contact with liquid crystal research.

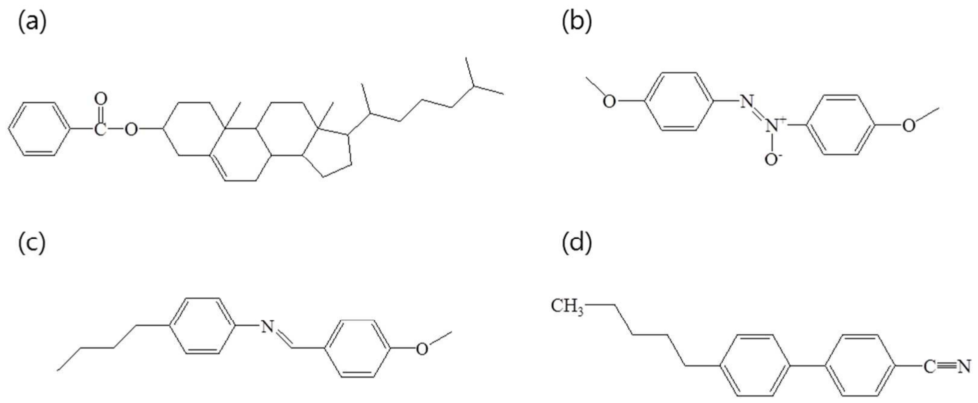

Fig. 1 Molecular structure of the typical LC: (a) cholesteryl benzoate, (b) p-azoxyanisole, (c) 4-methoxybenzylidene-4-butylaniline (MBBA), (d) 4-pentyl-4'-cyanobiphenyl (5CB).

Until 1969, the first room-temperature nematic substance, 4-methoxybenzylidene-40-butylaniline (MBBA) (Fig. 1c), was synthesized by Hans Kelker.[8] This material became one of the most heavily researched materials in the LC field of study. Additional milestones in the development of LC materials were reported as below. In 1973, George Gray synthesized a new class of LCs, which continues to be commercially important today: 4-n-alkyl-4'-cyanobiphenyl (CB, n=5-8). An example of this type of LC, 4-pentyl-4'-cyanobiphenyl (5CB), is illustrated in Fig. 1d.[9] Along with Ken Harrison and the UK Ministry of Defense (UK MOD) located at R. R. E. Malvern, Gray led design efforts for materials that were rapidly adopted for use in small LCDs for electronic devices. Then, W. MacMillan[10] and R. Meyer[11] proposed the mean-field theory for smectics in 1974.

In 1991, Pierre-Gilles de Gennes, a theoretical physicist working at the University of Paris XI in France, became interested in LCs and soon found amazing analogies between LCs and superconductors as well as magnetic materials, and received the Nobel Prize in physics "for discovering that methods developed for studying order phenomena in simple systems can be generalized to more complex forms of matter, in particular to liquid crystals and polymers".

The future of LCs has just begun. There are still many unsolved physical problems to investigate. LC materials are still used as a key component in simple inexpensive displays for common calculators and mobile phones. As research in this field continues and as new applications are developed, LCs will play an important role in chemistry, physics, biology, medicine, electronic engineering, and many other fields. Today, LCs are finding new applications in detection technology. In this review, we look at LCs as emerging materials for use in real time detection. New LC materials and devices will no doubt drive forward new research in these fundamental and applied sciences.

3. LCs and surfactants

Nematic LCs are composed of calamitic or rod-like organic molecules which have no positional order, but they self-align to have long-range directional order with their long axes roughly parallel.[12] Nematic LCs are characterized by their director field, $\vec{n}$, which can be seen using polarized optical microscopy. A number of previous researchers have reported the influence of surfactants adsorbed at the interface between the liquid crystal layer and the aqueous phase on the orientation of LCs.[13-15]

A systematic study of the anchoring of nematic LCs in contact with the aqueous phase containing surfactants has shown that the orientation of LCs was affected by its molecular architecture, alkyl chain length and concentration of surfactant.[16] A surfactant responds to the presence of LCs at the LC-aqueous interface by extending its non-polar alkyl chain homeotropically into alignment with the LC, causing the LC molecules to align in a homeotropic orientation (Fig. 2a). This homeotropic orientation is called a radial configuration when in LC droplets (Fig. 3a). LC droplets in this configuration have a point hedgehog disclination at the droplet center. Examples of surfactants that work this way include bolaform surfactants, which are ionic surfactants like sodium dodecyl sulfate (SDS) and dodecyltrimethylammonium bromide (DTAB).[17] However, polyvinylalcohol (PVA) or polyvinylpyrrolidone (PVP) adsorb at the interface in a more or less random coil conformation, imposing tangential anchoring at the surface. This conformation leaves the LC molecules in a planar orientation (Fig. 2b), which is called a bipolar configuration in LC droplets (Fig. 3b). This bipolar configuration then creates two point defects, referred to as “boojum” when occurring in LC droplets.[18-20] The most favorable configuration at an interface occurs when a polar phase such as water is used. An example of the experimental geometry used to create stable interfaces between aqueous phases and thermotropic LCs is shown in Fig. 4.[13]

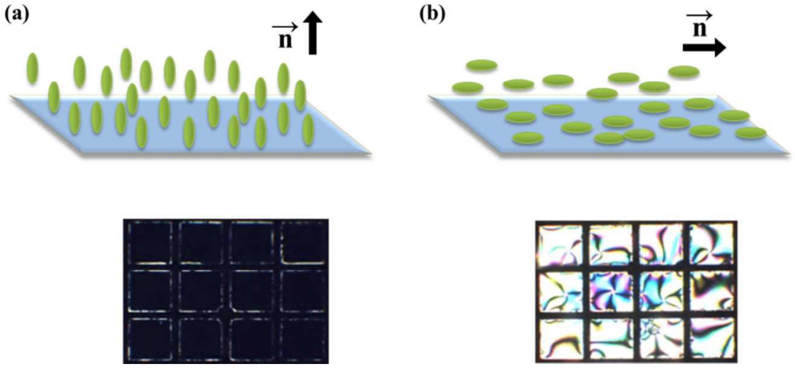

Fig. 2 Schematic representation of (a) homeotropic and (b) planar anchoring of LC molecules on a solid substrate

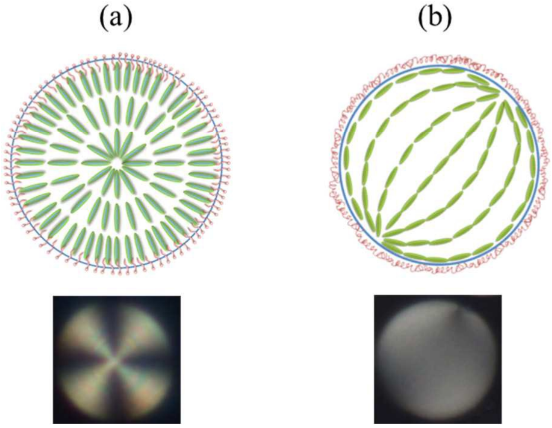

Fig. 3 Schematic representation of a typical LC droplet orientation: (a) radial, (b) bipolar.

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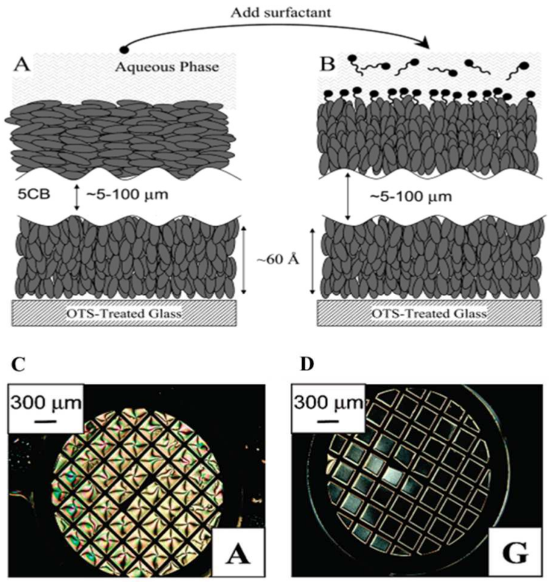


Fig. 4. A–B) Schematic illustration of the director profiles of 5CB induced by adsorption of SDS at the 5CB-aqueous interface: (A) SDS-free interface (planar anchoring of the LC at the interface with the aqueous phase) ; (B) SDS-laden interface (homeotropic anchoring of the LC at the interface with the aqueous phase). Note that the orientation of the 5CB at the grid surface is normal to the grid-5CB interface. C–D) Optical images (crossed polars) of 5CB confined to a copper grid with a spacing of 292 µm that was supported on an OTS-coated glass slide and immersed under pure water (C) or an aqueous solution of 2.2 mM SDS (D). Reprinted with permission from ref. 13. Copyright (2002) American Chemical Society.

In addition, J M Brake et al.[16] explained that the decreased bulk concentration of SDS and DTAB anchored at the interface changed the orientation of the LC molecules from planar to homeotropic. Hence, the dominant role of the surfactant headgroup is that of determining the interfacial density of the adsorbed surfactant (via headgroup-headgroup repulsion). Surfactants with short aliphatic chain lengths did not cause homeotropic anchoring of 5CB at any bulk concentrations of surfactant. The choice of surfactant is quite important because it will influence the alignment of the director at the interface and, later, when used in an actual detection device.

4. LCs and polyelectrolytes

The interactions of species at the LC/water interface result in variation of the LC director that causes detection of chemical and biological events occurring at the surface in contact with the LCs.[21-25] There has been recent interest in extending the application of LCs to imaging the molecular ordering of self-organized systems.[26-31] For this application, the interface of the LC was modified by adsorbing surfactants or polymers. Properties of these physically adsorbed species such as molecule density,[32] charge[30] and pH[33, 34] may accomplish this change in LCs, resulting in a different orientation.[35, 36] Hence, such chemically modified LC droplets were found to be a more useful option for the detection of chemicals and biological species.

4.1. Homopolymers as polyelectrolytes

Recently, Jianhua Zou et al.[30] reported that negatively charged poly(styrenesulfonate sodium salt) (PSS) and positively charged poly(diallyldimethylammonium chloride) (PDADMAC) multilayer-coated LC droplets had been successfully prepared. These materials can trigger bipolar/radial orientation transitions inside 5CB droplets (shown in Fig. 5, 6).

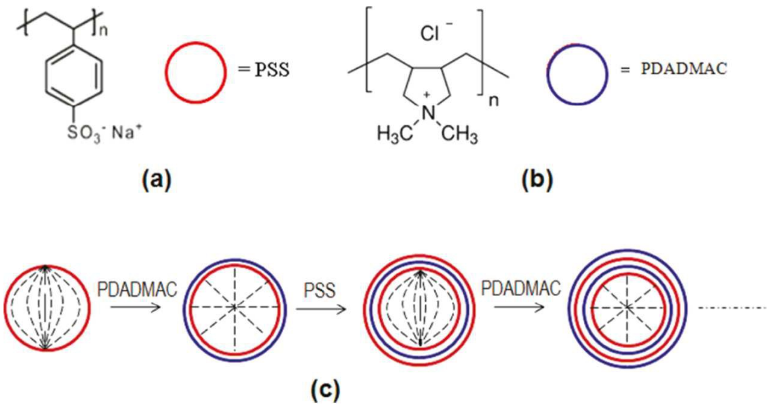


Fig. 5 (a) Chemical structures of poly(styrenesulfonate sodium salt) (PSS), (b) poly(diallyldimethylammonium chloride) (PDADMAC), and (c) a schematic illustration of the alternating bipolar/radial transitions of 5CB in droplets triggered by the layer-by-layer coating of PSS and PDADMAC on the droplet surface. Reprinted with permission from ref. from ref. 30. Copyright (2011) American Chemical Society.

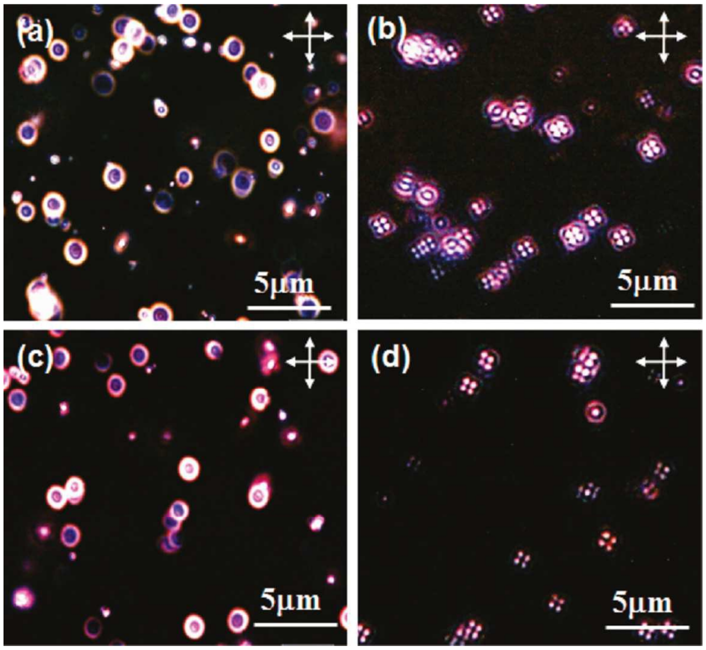


Fig. 6 (a) Polarizing optical microscopy images of poly(styrenesulfonate sodium salt)(PSS)-coated 5CB droplets, (b) poly(diallyldimethylammonium chloride)(PDADMAC)/PSS-coated 5CB droplets, (c) PSS/PDADMAC/PSS-coated 5CB droplets, and (d) (PDADMAC/PSS)$_2$-coated 5CB droplets. All images were taken in water. The direction of the polarizer and analyzer is indicated by white arrows. Reprinted with permission from ref. from ref. 42. Copyright (2011) American Chemical Society.

The orientational transition was found to be dependent on the amount of dendrimer coated on LC droplets. Hence, the sensitivity of the transition from bipolar to radial could be controlled using different amounts of the electrolyte or dendrimer on the surface of the LC (Fig. 7).[30] The layer-by-layer deposition of material for the modification of LC droplet surfaces was the easiest and most flexible approach, as it provided opportunities to deposit different materials, e.g., polymers,[31] proteins,[37] DNA,[38] multivalent cations,[39] and anions.[40] The surface of the LC provided ample opportunities for transformation of interfacial interactions and events[41-44] in ways for detection and quantification by analyzing orientational transitions in the LCs. The properties of LC emulsions in real-time detection depend on their size and topological defects. Monodispersed LC emulsions of different sizes and topologies have been prepared and characterized for their stability by containing a single droplet in a core-shell geometry[45] or by using the microfluidics technique.[46] A remarkable property of low molecular weight LCs is their ability to orient due to interactions at the interface. Clare et al.[47] calculated that a mass density of an oligopeptide of less than 1 ng/cm^2 can lead to a measurable change in the anchoring energy of 5CB. This result indicated that measurements of interfacial anchoring energies of LCs on surfaces may offer the basis of quantitative and label-free methods for real time detection of biomolecules on surfaces.

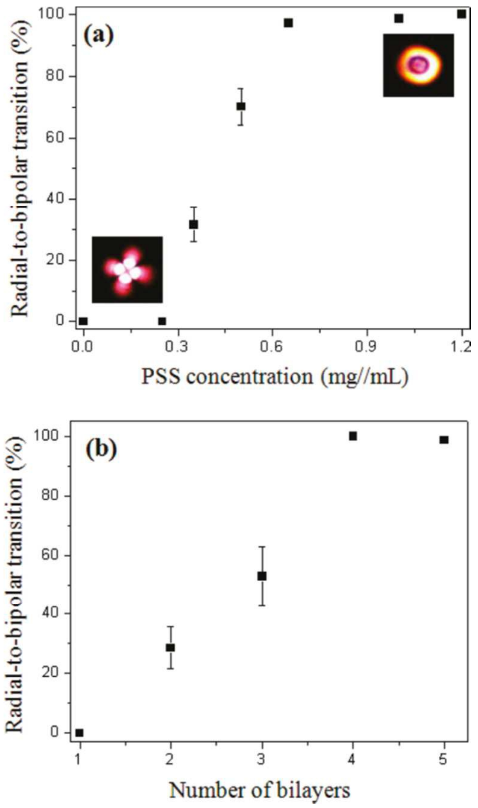


Fig. 7 (a) The director configuration transition of 5CB in poly(diallyldimethylammonium chloride)(PDADMAC)/poly(styrenesulfonate sodium salt)(PSS)-coated droplets after being exposed to PSS solutions with different concentrations for 20 min, (b) the director configuration transition of 5CB in PDADMAC/PSS multilayer-coated droplets after being exposed to a PSS solution with a concentration of 0.25 mg/mL for 20 min. The data points were obtained from averaging the result of 100 droplets for each sample. Reprinted with permission from ref. from ref. 30. Copyright (2011) American Chemical Society.

4.2. Copolymers as polyelectrolytes

Over the past ten years, researchers have shown a great interest in the synthesis of amphiphilic block copolymers due to their various applications in both academic and industrial settings. Block copolymers containing a polyelectrolyte block carrying ionizable groups with electrostatic charges have been widely studied and even incorporated into sensors.[48, 49] Abbott and co-workers[21] reported an amphiphilic diblock copolymer functionalized with hydrophobic (N-decyl acrylamide) and hydrophilic (N-{3-(dimethylamino) propyl} acrylamide) side groups that assembled at the aqueous/LC interface. Amphiphilic diblock copolymers were designed to anchor at the aqueous/5CB interface and respond reversibly to changes in the pH of the aqueous phase, resulting in an orientational change, which can be observed under a polarized microscope. Additionally, 5CB assembled with polyacrylic acid block liquid crystalline polymers have been used to facilitate examination of the effects of diverse stimuli, which has been reported by Park et al.[33, 50, 51] A compact coil of hydrophilic polyacrylic acid (PAA) block (e.g., at pH = 2) could spread over a small area on the aqueous/LC interface. Also, the connected hydrophobic poly(4-cyanobiphenyl-4-oxyundecylacrylate) (LCP) block might be miscible with 5CB, so that there are extensive interactions between 5CB and the LCP block (see Fig. 8, left). The LCP block (perpendicular to the main chain) would therefore be parallel to the interface, increasing the usual assembling ability at an aqueous/LC interface. However, the expanded coil of the PAA block (e.g., at pH = 12) would spread over a larger area on the interface, and the connected LCP block might relax and adopt an oblate configuration, resulting in LCs vertical to the interface (Fig. 8, right).[33]

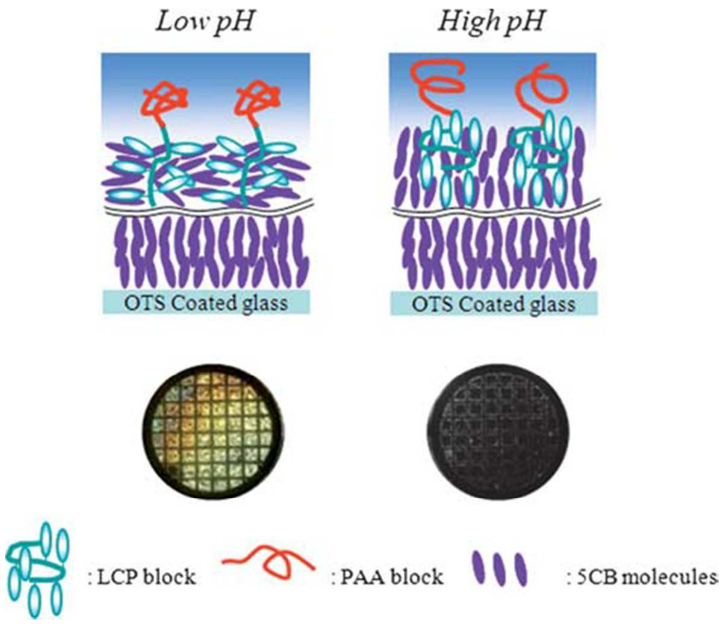


Fig. 8 A schematic diagram of director orientation in a cell, indicating the conformation of the polyacrylic acid (PAA)-b-poly(4-cyanobiphenyl-4-oxyundecylacrylate) (LCP) on an aqueous 5CB interface at pH 2 (left) and pH 12 (right). Reprinted with permission from ref. 33. Copyright (2010) Royal Society of Chemistry.

4.3. Electro-optical responses to polymer-encapsulated LCs

Electro-optical devices based on two- and three-dimensional arrays of polymer-encapsulated nematic LCs have been developed for large area flexible displays on plastic substrates.[43, 52-54] The polymer-dispersed LC (PDLC) devices switch reversibly between strongly scattering and transparent states by the application of large electrical fields in the droplets. In the off-state, the PDLC appears opaque as they strongly scatter light due to a mismatch of the refractive index between the LC droplets and the polymer matrix. In the presence of an electrical field, however, PDLCs becomes transparent because they allow light to pass due to matching of refractive indices of the LC and polymer.[55] Yu-Tse Lai et al.[56] reported a novel gas detector that uses a sensing film consisting of a PDLC doped with carbon nanotubes (CNT) for acetone detection (see Fig. 9). Fig. 9b shows a schematic representation of the CNT orientation in the CNT-PDLC-sensing film before chemical gas absorption. The orientations of CNTs and LC molecules are aligned parallel to the substrate because the LC media normally are strongly anchored to the CNT surface.[57] Consequently, the concentrations of chemical or biological agents that change the orientation of the LCs can be detected by measuring the conductivity of the CNT-LC material along a specific direction. Therefore, as shown in Fig. 9c, the gas molecules permeate through the CNT-PDLC film, and when the sensor is exposed to these gas molecules, the gas molecules destroy the alignment of the LC phase, resulting in an isotropic liquid phase. The gaseous acetone can be easily detected by measuring the changes in the electrical resistance of the sensing film. A linear sensor response was achieved for gas concentrations from 100 ppm (0.65% resistance change) to 1500 ppm (20.15% resistance change) and the response time was approximately 32 s. Hence, PDLCs have been developed as a shear stress sensor that offer many advantages over conventional single-point measurement systems, offering an ideal 2-dimensional mapping of shear stresses across a surface and showing a great signal-to-noise ratio with a high temporal bandwidth. Furthermore, the PDLCs allow for a reversible sensor that is self-adherent to testing surfaces.[58-60]

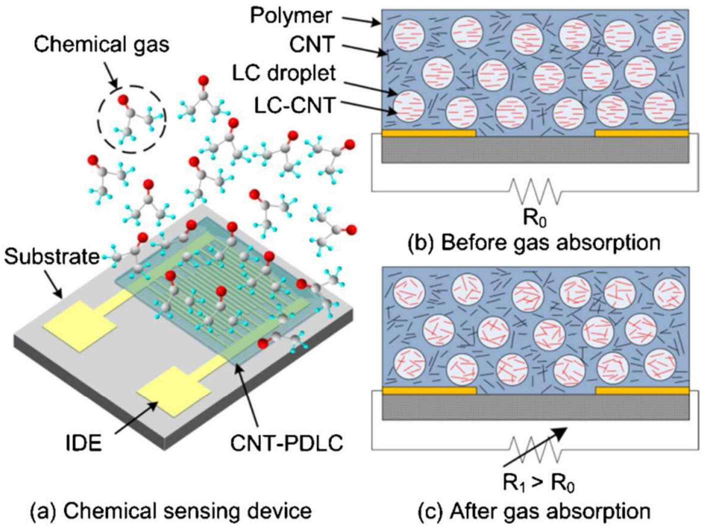


Fig. 9 Schematic diagram of (a) carbon nanotube (CNT)-polymer-dispersed liquid crystal (PDLC) chemical sensing device, (b) random LC droplets in a polymer and the orientation of CNT-LC, and (c) the sensor reactions when the CNT-PDLC material absorbs chemical gas. The CNT-conducting networks within the CNT-PDLC film are rearranged. Reprinted with permission from ref. 56. Copyright (2014) The Institute of Electrical and Electronics Engineers.

Cholesteric liquid crystal (CLC) is a type of the nematic liquid crystal, in which the LC molecules are ordered in a helical pattern.[61, 62] It is well known that CLCs have a unique optical property, selective reflection in a wavelength due to their helical structure.[63] When the wavelength of the reflected light corresponds to the visible light, the CLC appears iridescent colors to the naked eye.[64] Past studies have demonstrated the utilization of functional CLCs as portable and low-cost detection methods for volatile organic compounds (VOCs).[65, 66] Sutarlie et al.[67] reported the utility of a colorimetric polymer stabilized cholesteric liquid crystal (PSCLC) array for detecting vaporous amines. The addition of polymer supports the fluid CLC and increases its portability. The PSCLC with miscellaneous polymer concentrations (5–20% w/w) is made into an array which shows visible color changes upon exposure to 400 parts-per-million (ppm) octylamine vapor at 23–35 ℃. Intriguingly, PSCLC shows stronger response to vapors through hydrogen bonding with cholesteryl derivatives such as primary amine over secondary amine, tertiary amine, ester, aldehyde, and alkane having similar molecular weights (Fig. 10). Thin films of PSCLC also show capability to detect vapor with faster response times and better reversibility at room temperture. Hence, they can be coated on windows or safety goggles to offer real-time, power free protection against amine vapors.

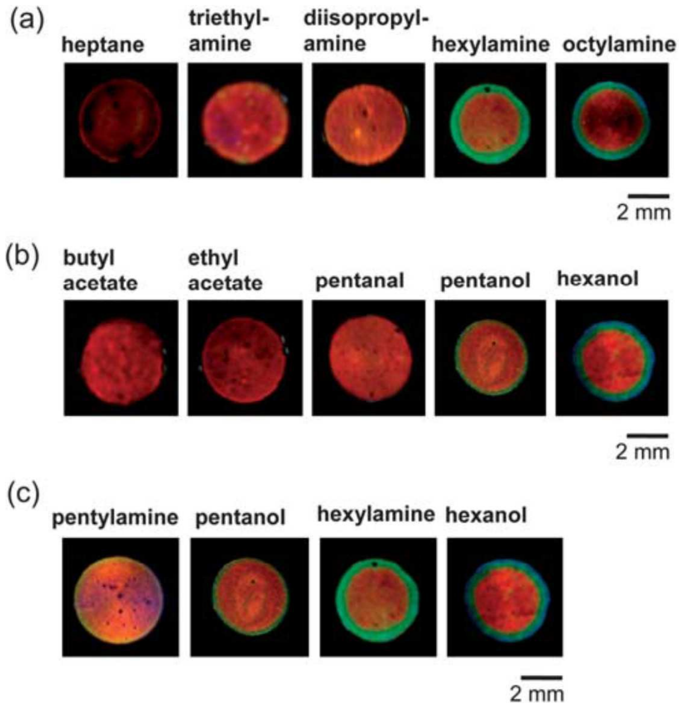


Fig. 10 Response of PSCLC (20% NOA61) to a variety of organic vapors at 400 ppmv including (a) alkane and various amines; (b) esters, aldehyde, and primary alcohol vapors. (c) Comparison of the colorimetric response of PSCLC (20% NOA61) to primary amine and primary alcohol vapors of similar molecular weight at 400 ppmv. Reprinted with permission from ref. 67. Copyright (2010) Royal Society of Chemistry.

In addition, Sutarlie et al.[68] reported a new sensing utilization of a thin layer of a polymer dispersed cholesteric liquid crystal (PDCLC) or a free CLC separated from the microfluidic device by using a thin film of poly(dimethylsiloxane) (PDMS) for monitoring ethanol inside microfluidic channels. They show distinct colorimetric response to ethanol solutions with a detection limit of 4% (v/v). These microfluidic channels with embedded PDCLC or embedded CLC also have potential for detecting other VOCs which are difficult to detect by using other chemical sensors.

5. LCs and biosensors

5.1. Detection of microorganisms

Brake et al.[16] demonstrated the detection of biomolecular interactions at fluid interfaces decorated with self-assembled phospholipid monolayers between LCs and aqueous solutions. Specific binding and enzymatic events could cause reorganization of the phospholipid membranes and result in a change in the orientation of the LCs. Additionally, poly(allylamine hydrochloride) (PAH)/poly(styrenesulfonate sodium) (PSS) multilayer-coated LC droplets have been used successfully in detection of lipid-enveloped viruses.[69] The orientational transition in the LC is due to the transfer of lipids from the viruses to the PAH/PSS multilayer-coated LC droplets (Fig. 11).

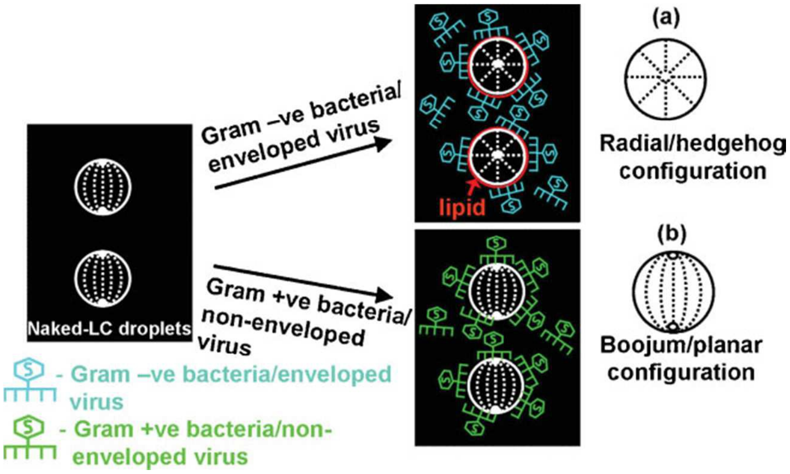


Fig. 11 Schematic representation of the interaction of viruses or bacteria with naked LC emulsions. The cartoons depict a) radial and b) bipolar configurations of LC droplets. Reprinted with permission from ref. 69. Copyright (2009) John Wiley and Sons.

Interfacial interactions have been a basis for molecular screening of diseases, toxins in food, narcotics in blood, and novel drugs. Most of these interfacial interactions and events depend on the immobilization of specific proteins that control ligand-receptor interactions (Fig. 12).[70, 71] Yoon et al.[72] reported a ligand-receptor interaction sensor for detection of KB cancer cells (mouth epidermal carcinoma cells). 5CB LC molecules were encapsulated by folic acid-conjugated block copolymers (PS-b-PAA-FA) and sodium dodecyl sulfate (SDS) as a mediator to cause an orientational change from radial to bipolar when contacted with KB cells, which has a specific folate receptor on its membrane as shown in Fig. 12. In addition, to confirm the selectivity of folate ligand-anchored 5CB microdroplets for recognition of KB cancer cells in the presence of other control cells, a set of co-cultured experiments was done in a phosphate-buffered saline solution (PBS, pH 7.4) at 30 °C in the presence of 5% CO_2 for 3 h by incubating LC microdroplets with KB cancer cells with a mixture of fibroblast (FB) and osteoblast (OB) cells, which were stained with methylene blue to distinguish[73] them from KB cancer cells (Fig. 13). The interaction of a KB cell (white) with a LC microdroplet induced the orientational transition from radial to bipolar is shown by the circle on the top side of the micrograph in Fig. 13a and 13b, whereas the interaction of control cells (blue) with LC microdroplets remained ineffective in inducing any orientational transition in LC microdroplets as shown by the circle on the bottom of the micrograph. Thus, folate ligand-anchored LC microdroplets have shown a potential for use in in-vitro detection of KB cancer cells in the early stage of tumor development.

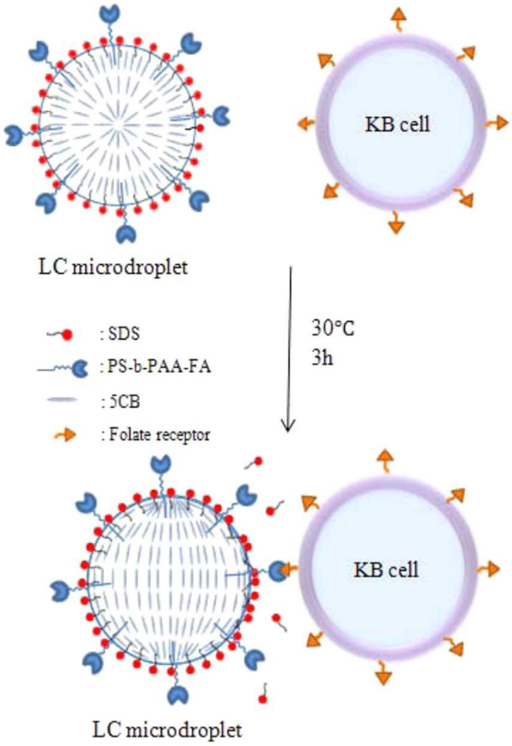


Fig. 12 KB cancer cell (mouth epidermal carcinoma cell) interactions with LC microdroplets containing folic acid-conjugated block copolymers (PS-b-PAA-FA). Reprinted with permission from ref. 72. Copyright (2014) American Chemical Society.

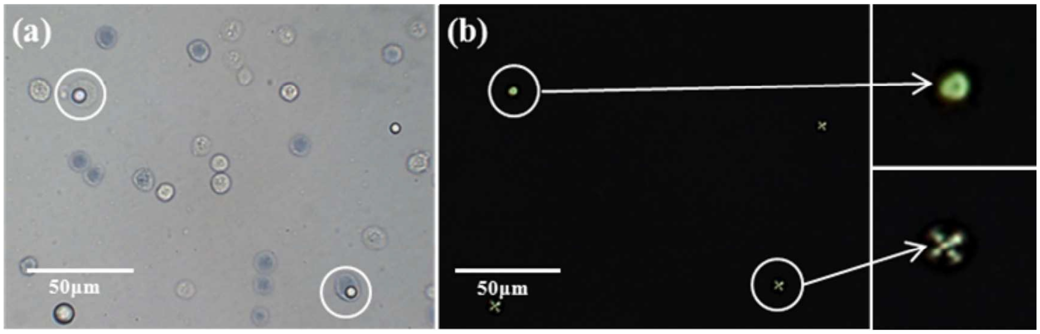
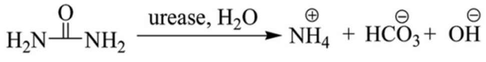


Fig. 13 (a) Bright field micrograph of LC microdroplets incubated for 3 h with KB cancer cells (mouth epidermal carcinoma cells) and methylene blue-stained fibroblast (FB) and osteoblast (OB) cells. The contact of LC microdroplets with KB cells is shown by circles at left top and methylene blue-stained FB or OB cells at bottom right, and (b) polarized light micrograph of LC microdroplets (2.1 × 10^6/mL) after contact for 3 h with KB, FB, and OB cells at a total density of 8000 cells/mL in 1:1:1 ratio. The polarized light micrograph of LC microdroplets after contact with KB cells for 3 h showed a bipolar configuration (left top circle) and a radial configuration after contact with FB or OB cells (right bottom circle). Conditions of tests: temperature 30 °C, pH 7.4 and medium PBS for all images. Reprinted with permission from ref. 72. Copyright (2014) American Chemical Society.

5.2. Detection of biomolecules

The long-range orientational ordering transition and fluidity of LCs triggered by the response of the assembled molecules at the LC/water interface to external stimuli has received a great deal of attention due to its application to biosensors. Surfactant-decorated LC-based sensors have been developed to detect competitive binding of cholic acid,[74] specific enzymatic reactions,[75-81] protein absorption,[82-85] environmental pollutants,[86, 87] antigen-antibody immunoassay,[1, 88, 89] DNA hybridization[90, 91] and DNA interaction with immobilized oligonucleotides.[92, 93] Mashooq Khan[94] reported a LC-based urea biosensor functionalized with mixed PAA and 4-cyanobiphenyl-4-oxyundecylacrylate brushes, which was tested for stability, enzyme activity (see Scheme 1), and sensitivity towards urea detection. A transmission electron microscopy (TEM) grid filled with 5CB on an octadecyltrichloro silane-coated glass substrate in aqueous media was prepared and then coated with poly(acrylic acid-b-4-cyanobiphenyl-4-oxyundecylacrylate) (PAA-b-LCP) at the aqueous/LC interface at which immobilizing urease was covalently bound to the PAA chains. Urea was detected from the planar-to-homeotropic (P–H) orientational transition of 5CB molecules at concentrations as low as 5 mM by polarized optical microscopy with crossed polarizers (Fig. 14).



$$H_2N-\overset{O}{\overset{\|}{C}}-NH_2 \xrightarrow{\text{urease, } H_2O} \overset{\oplus}{NH_4} + H\overset{\ominus}{CO_3} + \overset{\ominus}{OH}$$

Scheme 1 Hydrolysis of urea by urease.

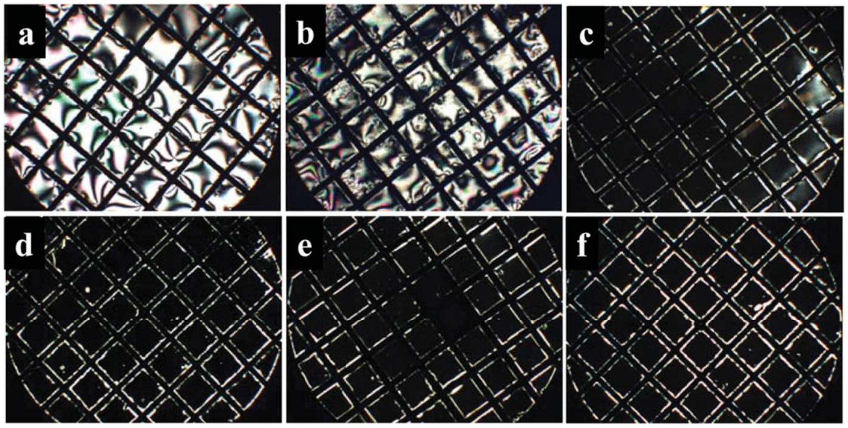


Fig. 14 Polarized Light Microscopy (POM) images of transmission electron microscopy (TEM) grids under crossed polarizers with different urea concentrations (C_0s) of (a) 2, (b) 3, (c) 5, (d) 8, (e) 20, and (f) 80 mM. Reprinted with permission from ref. 94. Copyright (2014) Royal Society of Chemistry.

The immobilized proteins can have random or well-defined orientations depending on the physical binding/chemical linkages between the functionalized surfaces and the proteins. However, a well-defined orientation of the protein is found useful to prevent denaturation and preserve the biological functions of the immobilized proteins.[78, 95, 96] Well-defined proteins are immobilized in a number of ways such as i) chemoselective immobilization via Staudinger ligation, Diels-Alder cycloaddition reactions, or native chemical ligation, and ii) fusion protein immobilization via popular fusion tags. The orientations of LCs are very sensitive to minute changes on the surfaces, which can be amplified to the LC bulk phase up to 100 μm within tens of milliseconds, and the orientation of the birefringence can be readily seen under crossed polarizers.[21]

6. Conclusion

LC materials and technology can contribute to the assembly of label-free, high-sensitivity real-time detectors without the need for complex and expensive instrumentation. LC materials have been found to be simple, convenient, and efficient in making sensing devices for transduction of various chemical and biological events into optical responses visible by the naked eye. LC-based sensors were found to be useful in a variety of sensing applications under ambient light conditions, including the detection of environmental pollutants, enzymatic reactions, protein interactions, ligand-receptor interactions, antigen-antibody immunoassay interactions, and DNA hybridization. LC-based sensing techniques are simple and useful for development of portable, low-cost screening assays for rapid evaluation of samples away from the central laboratory.

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Ding Wang

Ding Wang is an engineering graduate student at the School of Applied Chemical Engineering, Major in Polymer Science and Engineering, Kyungpook National University. She received her BS degree in the School of Chemistry and Materials Science at Nanjing Normal University. In fall 2013, she began her graduate studies with Prof. Inn-Kyu Kang. Her research interest lies in the application of liquid crystal biosensor.

Soo-Young Park

Soo-Young Park is a professor in the Department of Polymer Science and Engineering at the Kyungpook National University (KNU). He obtained his Ph.D. degree in the Department of Macromolecular Science at the Case Western Reserve University in 1998, and joined in the Department of Polymer Science and Engineering at the KNU in 2002 as a professor. He is currently a director of Polymeric Nano Materials Laboratory (PNML) and a principal investigator of Basic Research Laboratory (Ultra-

sensitive LC-based Sensors) sponsored by Korean Research Foundation. He has published more than 120 articles and his research is focused on structure analysis using WAXS/SAXS/SANS, nanocomposites, and liquid crystal sensors.

Inn-Kyu Kang

Inn-Kyu Kang is a professor of Department of Polymer Science and Engineering at the Kyungpook National University. He obtained his Ph.D. degree in Polymer Chemistry Department at Kyoto University in 1987, and joined in the Department of Polymer Science and Engineering, Kyungpook National University in 1988 as a professor. He is currently a director of Center for Intelligent Hybrid Nanomaterials and Processes supported by the Brain Korea 21+ National Program. He has published more than 190 articles and his research is focused on surface modification, nanofiber scaffolds, functionalization of nanoparticles, and liquid crystal sensors.

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