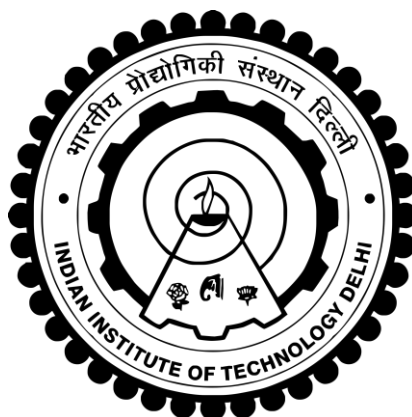


**STUDIES ON THE NEMATIC PHASES OF FLEXIBLE
AND RIGID BENT-CORE LIQUID CRYSTALS -
EXTENSION TO POLYMERS FOR ENERGY
HARVESTING APPLICATIONS**

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**DEPARTMENT OF PHYSICS
INDIAN INSTITUTE OF TECHNOLOGY DELHI
OCTOBER 2022**

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EXTENSION TO POLYMERS FOR ENERGY
HARVESTING APPLICATIONS**

by

SOURAV PATRANABISH

Department of Physics

Submitted

in fulfilment of the requirements of the degree of Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

OCTOBER 2022

Dedicated to my Parents and Supervisor

CERTIFICATE

This is to certify that the thesis entitled, “**Studies on the nematic phases of flexible and rigid bent-core liquid crystals - extension to polymers for energy harvesting applications**”, being submitted by **Mr. Sourav Patranabish** to the Indian Institute of Technology Delhi for the award of the degree of **Doctor of Philosophy** in Physics is a record of bonafide research work carried out by him. He has worked under my supervision and guidance, and has fulfilled the requirements for the submission of this thesis, which to the best of my knowledge has reached the requisite standard.

The contents of this thesis have not been submitted in part or in full to any other university or institute for the award of any degree or diploma.



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LIST OF PUBLICATIONS

Journal(s)

1. **Sourav Patranabish**, Golam Mohiuddin, Nazma Begum, Atiqur R. Laskar, Santanu K. Pal, Nandiraju V. S. Rao, and Alok Sinha, “Cybotactic Nematic Phase of Achiral Unsymmetrical Bent-Core Liquid Crystals – Quelling of Polar Ordering and the Influence of Terminal Substituent Moiety”, *J. Mol. Liq.*, **257**, 144 (2018).
2. **Sourav Patranabish**, Yiwei Wang, Alok Sinha, and Apala Majumdar, “One-dimensional theoretical analysis of coupling and confinement effects on the cybotactic clusters of bent-core nematic liquid crystals”, *Phys. Rev. E*, **99**, 012703 (2019).
3. **Sourav Patranabish**, Yiwei Wang, Alok Sinha, and Apala Majumdar, “Quantum-dots-dispersed bent-core nematic liquid crystal and cybotactic clusters: Experimental and theoretical insights”, *Phys. Rev. E*, **103**, 052703 (2021).
4. **Sourav Patranabish**, Sameer Dhawan, V. Haridas, and Alok Sinha, “Designer peptide-PVDF composite films for high performance energy harvesting”, *Macromol. Rapid Commun.*, **2200493** (2022).
5. **Sourav Patranabish**, Alok Sinha, Madhu B. Kanakala, and C. V. Yelamaggad, “Nematic twist-bend phase of a bent liquid crystal dimer: field-induced deformations of the helical structure and macroscopic polarization”, *J. Phys. Condens. Matter*, **34**, 465101 (2022).

Patent(s)

1. Alok Sinha, V. Haridas, **Sourav Patranabish**, and Sameer Dhawan, “Peptide-based mixture composition for piezoelectric energy harvesting and a method of fabricating the device”, **IN Patent application No. 202211023426** (2022).

National and International Conferences

1. **Sourav Patranabish**, Aloka Sinha, Golam Mohiuddin, Nazma Begum, and Nandiraju V. S. Rao, “Evidence of possible biaxiality in a bent-core liquid crystal compound for faster switching display applications,” in *13th International Conference on Fiber Optics and Photonics (PHOTONICS 2016)*, IIT Kanpur, India, December 04-08 (2016).
2. **Sourav Patranabish**, Aloka Sinha, Golam Mohiuddin, and Nandiraju V. S. Rao, “Study of Electro convection Patterns Observed in Four-Ring Bent-Core Liquid Crystal Compounds”, in *24th National Conference on Liquid Crystals (NCLC-2017)*, IISER Mohali, India, October 11-13 (2017).
3. **Sourav Patranabish**, Yiwei Wang, Aloka Sinha, and Apala Majumdar, “One-dimensional Landau-de Gennes model for bent-core nematic liquid crystals: effect of confinement, coupling and extension to nano-doped systems”, in *ICERM Workshop on Numerical Methods and New Perspectives for Extended Liquid Crystalline Systems*, Brown University, USA, December 09-13 (2019).

International Conferences (Not included in the thesis)

1. Ram Ashish Yadav, **Sourav Patranabish**, and Aloka Sinha, “Liquid Crystal Based Ultraviolet Sensor”, in *14th International Conference on Fiber Optics and Photonics (PHOTONICS 2018)*, IIT Delhi, India, December 12-15 (2018).

Abstract

Liquid crystals (LCs) are an indispensable part of our day-to-day life – they are widely regarded as the material for modern-day electro-optic devices and displays. Lower control voltages, high birefringence, and anisotropic properties of LCs make them an excellent candidate for optical and electro-optic devices. Among the vast pool of exotic mesophases offered by LCs (e.g., nematic (N), smectic-A (SmA), smectic-C (SmC), smectic-C* (SmC*), blue phases (BP)), the nematic phase has been proven to be ideal from the application point of view because of its reduced viscosity and more dynamic control over the others. The LC materials used in present-day devices have a rod-like molecular shape, and they are called the calamitic LCs. Over the last few years, a new kind of LCs, called the banana-shaped or bent-core LCs, have gained significant attention owing to their unique and interesting properties, such as polarity, chirality and biaxiality, that are envisaged as the paving stones for the next-generation faster-switching displays. Among these unique features, polarity is regarded as the most important one because it causes a ferroelectric-like behaviour in the nematic phase with sub-millisecond switching. A key method for experimentally realizing this ferroelectric-like polar order is to selectively orient the locally polar, highly ordered microstructures, called the cybotactic clusters, in the nematic phase of bent-core LCs. Also, the nematic phases of bent-core LCs manifest several unusual physical properties, such as, giant flexoelectric response, low-frequency dielectric relaxation, and unusual electro-convection scenarios, which may be related to the presence of cybotactic clusters. Another interesting variant of the nematic phases of bent-core LCs have recently been discovered, called the twist-bend nematic (N_{tb}) phase, which may find applications in tunable diffraction gratings and reflective displays. Moreover, from a structure-property relationship point of view, minute variations in the molecular structure and terminal or lateral substituents may largely affect the resulting LC mesophases of bent-core LCs and their associated properties.

Therefore, the broad aim of the thesis is to investigate the different physical properties of bent-core liquid crystals (LCs), especially in their nematic (N) phases, to develop a better understanding of the underlying ferroelectric nature, the formation of cybotactic clusters, and the influence of various internal and external factors on the formation of these clusters. The field-induced polarization behaviour in the twist-bend nematic phase is also investigated in its pure and nanoparticles doped variants. Towards the end of the thesis, piezoelectric energy harvesting application has been explored by using a lipidated pseudopeptide compound as efficient fillers in the polyvinylidene fluoride (PVDF) polymer matrix, and the potential application of LCs in such energy harvesting devices are also discussed.

The first two chapters of the thesis discuss the basic concepts, classifications, and properties of LCs, piezoelectricity, piezoelectric polymers, and the various experimental methods and techniques used. In the third chapter, we present a comparative study of three achiral, unsymmetrical, four-ring bent-core LC compounds bearing a long alkyloxy chain at one end and differing only in the terminal substituent moiety ($-\text{CH}_3$, $-\text{Cl}$, and NO_2) at the other end. The methyl and chloro substituted compounds manifest a cybotactic nematic phase while the nitro substituted compound shows only a layered smectic phase. Through a detailed experimental investigation, we establish that cybotactic clusters and polar end moieties, although a prerequisite for a ferroelectric-like response, do not necessarily result in a ferroelectric nematic phase. In chapter 4, we focus on the cybotactic clusters of bent-core nematic LCs and investigate the effects of coupling and confinement on the formation of these clusters from a theoretical analogue. We develop a phenomenological model for bent-core nematic LCs in the Landau-de Gennes (LdG) framework and demonstrate that an enhanced coupling invokes augmented formation of clusters in the LC bulk. We also observe that an enhanced coupling promotes a weak nematic-like order above the isotropic supercooling temperature, and that a systematic variation of the boundary conditions do not affect the cluster formation in the bulk. In chapter 5, we investigate the effects of CdSe/ZnS core-shell type spherical quantum-dots (QDs) dispersion on cybotactic clusters of the

bent-core nematic LCs. Experimentally, we observe that the incorporation of QDs result in reduced orientational order parameter, reduced cluster size, and increased activation energies. The reduction in cluster size is qualitatively estimated by the collective mode relaxation frequency ratio for the pure and doped LCs. We also complement our experimental observations with a modified, novel LdG-type free-energy for doped systems, built on the premises of our work in chapter 4. It provides validation to our models developed in these two chapters from an experimental viewpoint.

In chapter 6, we turn our attention to the twist-bend nematic phase of bent-core LCs. A flexible core bent-core LC (CB7CB) is studied in its nematic and twist-bend nematic phase in both pure and TiO_2 nanoparticles (NPs) dispersed variant. We observed a threshold-dependent polarization current response in both the phases of pure CB7CB due to field-induced reorientation of cybotactic clusters and the deformation of twist-bend helical structures. The studies in the NPs dispersed variant reveal that the net polarization has competing contributions from both ferroelectric-like and ionic origin (only at lower frequencies), but it becomes dominantly ferroelectric-like at higher frequencies. In chapter 7, we make an attempt to explore energy harvesting applications and discuss the possibilities of LC-assisted dynamic energy harvesting. As a first step, to demonstrate the proof of concept or viability, we use a lipidated pseudopeptide compound as efficient fillers in polyvinylidene fluoride (PVDF) polymer matrix to enhance the net ferroelectric and piezoelectric properties. We also demonstrate its application in mechanical energy harvesting by fabricating superior performing devices in a low-cost and facile fabrication route. Towards the end of this chapter, we briefly discuss the possibility of extension of this work to LCs, especially bent-core LCs with cybotactic clusters, as fillers in the light of their anisotropic nature, ferroelectric, flexoelectric, and piezoelectric properties. This direction will be explored as a promising future scope of the present thesis. The studies reported in this thesis open new avenues to explore bent-core LCs, especially in their nematic phase, from both fundamental and applied research point of view.

लिक्विड क्रिस्टल (एलसी) हमारे दिन-प्रतिदिन के जीवन का एक अनिवार्य हिस्सा हैं - उन्हें व्यापक रूप से आधुनिक इलेक्ट्रो-ऑप्टिक उपकरणों और डिस्प्ले के लिए सामग्री के रूप में माना जाता है। एलसी के कम नियंत्रण वोल्टेज, उच्च बायरफ्रिंग और अनिसोट्रोपिक गुण उन्हें ऑप्टिकल और इलेक्ट्रो-ऑप्टिक उपकरणों के लिए एक उत्कृष्ट उम्मीदवार बनाते हैं। एलसी (उदाहरण के लिए, नेमैटिक (एन), स्मेक्टिक-ए (एसएमए), स्मेक्टिक-सी (एसएमसी), स्मेक्टिक-सी * (एसएमसी *), ब्लू फेज (बीपी)), नेमैटिक द्वारा पेश किए गए अनोखे मेसोफेज के विशाल पूल में से चरण अपनी कम चिपचिपाहट और दूसरों पर अधिक गतिशील नियंत्रण के कारण आवेदन के दृष्टिकोण से आदर्श साबित हुआ है। वर्तमान उपकरणों में उपयोग की जाने वाली एलसी सामग्री में रॉड जैसी आणविक आकृति होती है, और उन्हें कलैमिटीक एलसी कहा जाता है। पिछले कुछ वर्षों में, एक नए प्रकार के एलसी, जिन्हें केले के आकार का या बेंट-कोर एलसी कहा जाता है, ने अपने अद्वितीय और दिलचस्प गुणों, जैसे कि ध्रुवता, चिरलिटी और द्विअक्षीयता के कारण महत्वपूर्ण ध्यान आकर्षित किया है, जिसकी परिकल्पना पेविंग स्टोन के रूप में की गई है। अगली पीढ़ी के तेज़-स्विचिंग डिस्प्ले के लिए। इन अनूठी विशेषताओं में, ध्रुवता को सबसे महत्वपूर्ण माना जाता है क्योंकि यह उप-मिलीसेकंड स्विचिंग के साथ नेमैटिक चरण में फेरोइलेक्ट्रिक जैसे व्यवहार का कारण बनता है। इस फेरोइलेक्ट्रिक-जैसे ध्रुवीय क्रम को प्रयोगात्मक रूप से साकार करने के लिए एक महत्वपूर्ण तरीका स्थानीय रूप से ध्रुवीय, उच्च क्रम वाले माइक्रोस्ट्रक्चर को चुनिंदा रूप से उन्मुख करना है, जिसे साइबोटैक्टिक क्लस्टर कहा जाता है, बेंट-कोर एलसी के नेमैटिक चरण में। इसके अलावा, बेंट-कोर एलसी के नेमैटिक चरण कई असामान्य भौतिक गुणों को प्रकट करते हैं, जैसे कि विशाल फ्लेक्सोइलेक्ट्रिक प्रतिक्रिया, कम आवृत्ति ढांकता हुआ छूट, और असामान्य इलेक्ट्रो-संवहन परिदृश्य, जो कि साइबोटैक्टिक क्लस्टर की उपस्थिति से संबंधित हो सकते हैं। बेंट-कोर एलसी के नेमैटिक चरणों का एक और दिलचस्प संस्करण हाल ही में खोजा गया है, जिसे ट्विस्ट-बेंड नेमैटिक (एनटीबी) चरण कहा जाता है, जो ट्यून करने योग्य विवर्तन झंझरी और परावर्तक डिस्प्ले में अनुप्रयोग पा सकता है। इसके अलावा, एक संरचना-संपत्ति संबंध दृष्टिकोण से, आणविक संरचना और टर्मिनल या पार्श्व प्रतिस्थापन में मिनट भिन्नताएं बड़े पैमाने पर बेंट-कोर एलसी और उनके संबंधित गुणों के परिणामस्वरूप एलसी मेसोफेज़ को प्रभावित कर सकती हैं।

इसलिए, थीसिस का व्यापक उद्देश्य बेंट-कोर लिक्विड क्रिस्टल (एलसी) के विभिन्न भौतिक गुणों की जांच करना है, विशेष रूप से उनके नेमैटिक (एन) चरणों में, अंतर्निहित फेरोइलेक्ट्रिक प्रकृति की बेहतर समझ विकसित करने के लिए, साइबोटैक्टिक क्लस्टर का गठन , और इन समूहों के गठन पर विभिन्न आंतरिक और बाहरी कारकों का प्रभाव। ट्विस्ट-बेंड नेमैटिक चरण में क्षेत्र-प्रेरित ध्रुवीकरण व्यवहार की जांच इसके शुद्ध और नैनोकणों के डोप वेरिएंट में भी की जाती है। थीसिस के अंत में, पॉलीविनाइलिडीन फ्लोराइड (पीवीडीएफ) पॉलीमर मैट्रिक्स में कुशल फिलर्स के रूप में लिपिडेटेड स्यूडोपेप्टाइड यौगिक का उपयोग करके पीजोइलेक्ट्रिक एनर्जी हार्वेस्टिंग एप्लिकेशन का पता लगाया गया है, और ऐसे ऊर्जा संचयन उपकरणों में एलसी के संभावित अनुप्रयोग पर भी चर्चा की गई है।

थीसिस के पहले दो अध्याय एलसी, पीजोइलेक्ट्रिसिटी, पीजोइलेक्ट्रिक पॉलिमर, और विभिन्न प्रयोगात्मक विधियों और तकनीकों के उपयोग की बुनियादी अवधारणाओं, वर्गीकरण और गुणों पर चर्चा करते हैं। तीसरे अध्याय में, हम तीन अचिरल, असममित, चार-अंगूठी बेंट-कोर एलसी यौगिकों का तुलनात्मक अध्ययन प्रस्तुत करते हैं, जो एक छोर पर एक लंबी एल्काइलॉक्सी श्रृंखला को प्रभावित करते हैं और केवल टर्मिनल प्रतिस्थापक भाग ($-\text{CH}_3$, $-\text{Cl}$, और NO_2) में भिन्न होते हैं। दूसरी तरफ। मिथाइल और क्लोरो प्रतिस्थापित यौगिक एक साइबोटैक्टिक नेमैटिक चरण प्रकट करते हैं जबकि नाइट्रो प्रतिस्थापित यौगिक केवल एक स्तरित स्मेक्टिक चरण दिखाता है। एक विस्तृत प्रायोगिक जांच के माध्यम से, हम उस सायबोटैक्टिक क्लस्टर और ध्रुवीय अंत मोअर्स को स्थापित करते हैं, हालांकि फेरोइलेक्ट्रिक जैसी प्रतिक्रिया के लिए एक शर्त, जरूरी नहीं कि फेरोइलेक्ट्रिक नेमैटिक चरण में परिणाम हो। अध्याय 4 में, हम बेंट-कोर नेमैटिक एलसी के साइबोटैक्टिक समूहों पर ध्यान केंद्रित करते हैं और सैद्धांतिक एनालॉग से इन समूहों के गठन पर युग्मन और रोक के प्रभावों की जांच करते हैं। हम लैंडौ-डी-जेन्स (एलडीजी) ढांचे में बेंट-कोर नेमैटिक एलसीयो के लिए एक अभूतपूर्व मॉडल विकसित करते हैं और प्रदर्शित करते हैं कि एक बढ़ाया युग्मन एलसी बल्क में क्लस्टर के संवर्धित गठन को आमंत्रित करता है। हम यह भी देखते हैं कि एक बढ़ाया युग्मन आइसोट्रोपिक सुपरकूलिंग तापमान के ऊपर एक कमजोर नेमैटिक-जैसे क्रम को बढ़ावा देता है, और यह कि सीमा की स्थिति का एक व्यवस्थित बदलाव थोक में क्लस्टर गठन को प्रभावित नहीं करता है। अध्याय 5 में, हम सीडीएसई/जेडएनएस कोर-शेल प्रकार गोलाकार क्वांटम-डॉट्स (क्यूडीयो) फैलाव के बेंट-कोर नेमैटिक एलसीयो के साइबोटैक्टिक समूहों पर प्रभावों की जांच करते हैं। प्रायोगिक तौर पर, हम देखते हैं कि क्यूडीयो को शामिल करने से ओरिएंटल ऑर्डर पैरामीटर कम हो जाता है, क्लस्टर आकार कम हो जाता है और सक्रियण ऊर्जा बढ़ जाती है। क्लस्टर आकार में कमी का अनुमान शुद्ध और डोपड

एलसी के लिए सामूहिक मोड छूट आवृत्ति अनुपात द्वारा गुणात्मक रूप से लगाया जाता है। हम अध्याय 4 में हमारे काम के परिसर में निर्मित डोपड सिस्टम के लिए एक संशोधित, उपन्यास एलडीजी-प्रकार मुक्त-ऊर्जा के साथ अपने प्रयोगात्मक अवलोकनों को भी पूरक करते हैं। यह प्रयोगात्मक दृष्टिकोण से इन दो अध्यायों में विकसित हमारे मॉडल को सत्यापन प्रदान करता है।

अध्याय 6 में, हम अपना ध्यान बेंट-कोर एलसी के द्विस्ट-बैंड नेमैटिक चरण की ओर मोड़ते हैं। एक लचीले कोर बेंट-कोर एलसी (सीबी7सीबी) का अध्ययन इसके नेमैटिक और द्विस्ट-बैंड नेमैटिक चरण में शुद्ध और TiO_2 नैनोपार्टिकल्स (एनपी) बिखरे हुए संस्करण दोनों में किया जाता है। हमने साइबोटैक्टिक समूहों के क्षेत्र-प्रेरित पुनर्संयोजन और मोड़-मोड़ पेचदार संरचनाओं के विरूपण के कारण शुद्ध CB7CB के दोनों चरणों में एक थ्रेशोल्ड-निर्भर ध्रुवीकरण वर्तमान प्रतिक्रिया देखी। एनपी के बिखरे हुए संस्करण में अध्ययन से पता चलता है कि शुद्ध ध्रुवीकरण में फेरोइलेक्ट्रिक-जैसे और आयनिक मूल (केवल कम आवृत्तियों पर) दोनों से प्रतिस्पर्धात्मक योगदान है, लेकिन यह उच्च आवृत्तियों पर प्रमुख रूप से फेरोइलेक्ट्रिक जैसा हो जाता है। अध्याय 7 में, हम ऊर्जा संचयन अनुप्रयोगों का पता लगाने का प्रयास करते हैं और एलसी-सहायता प्राप्त गतिशील ऊर्जा संचयन की संभावनाओं पर चर्चा करते हैं। पहले कदम के रूप में, अवधारणा या व्यवहार्यता के प्रमाण को प्रदर्शित करने के लिए, हम शुद्ध फेरोइलेक्ट्रिक और पीजोइलेक्ट्रिक गुणों को बढ़ाने के लिए पॉलीविनाइलिडीन फ्लुओराइड (पीवीडीएफ) पॉलीमर मैट्रिक्स में कुशल फिलर्स के रूप में एक लिपिडेटेड स्फूडोपेष्टाइड यौगिक का उपयोग करते हैं। हम कम लागत और आसान निर्माण मार्ग में बेहतर प्रदर्शन करने वाले उपकरणों का निर्माण करके यांत्रिक ऊर्जा संचयन में इसके अनुप्रयोग को भी प्रदर्शित करते हैं। इस अध्याय के अंत में, हम संक्षेप में इस काम के विस्तार की संभावना पर चर्चा करते हैं, विशेष रूप से साइबोटैक्टिक समूहों के साथ बेंट-कोर एलसी, उनके अनिसोट्रोपिक प्रकृति, फेरोइलेक्ट्रिक, प्लेक्सोइलेक्ट्रिक और पीजोइलेक्ट्रिक गुणों के प्रकाश में फिलर्स के रूप में। इस दिशा को वर्तमान थीसिस के एक आशाजनक भविष्य के दायरे के रूप में खोजा जाएगा। इस थीसिस में बताए गए अध्ययनों से बेंट-कोर एलसी का पता लगाने के लिए नए रास्ते खुलते हैं, विशेष रूप से उनके नेमैटिक चरण में, मौलिक और अनुप्रयुक्त अनुसंधान दोनों दृष्टिकोण से।

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LIST OF SYMBOLS AND ABBREVIATIONS

LC: Liquid crystal	TN: Twisted nematic
LCD: Liquid crystal display	BLC: Bent-core liquid crystal
TFT: Thin-film transistor	IPS: In-plane switching
LED: Light emitting diode	FLC: Ferroelectric liquid crystal
NLC: Nematic liquid crystal	LCPC: Liquid crystal polymer composite
SLM: Spatial light modulator	PSLC: Polymer-stabilized liquid crystal
PDLC: Polymer-dispersed liquid crystal	POM: Polarizing optical microscopy
5CB: 4-Cyano-4'-pentylbiphenyl	ITO: Indium tin oxide
DSC: Differential scanning calorimetry	PI: Polyimide
DI: Deionized water	IPA: Isopropyl alcohol
PR: Photoresist	DMM: Digital multimeter
LdG: Landau-de Gennes	QD: Quantum dot
NP: Nanoparticle	PVDF: Polyvinylidene fluoride
DFT: Density functional theory	SAXS: Small-angle X-ray scattering
XRD: X-ray diffraction	P-E loop: Polarization-electric field loop
VHR: Voltage holding ratio	UV: Ultraviolet
FWHM: Full width at half maximum	DSO: Digital storage oscilloscope
PLA: Polylactic acid	FSR: Force sensing resistor
EC: Electroconvection pattern	DMF: N,N'-Dimethylformamide
N: Nematic phase	N _{cyb} : Cybotactic nematic phase
N _{tb} : Twist-bend nematic phase	N*: Cholesteric / Chiral nematic phase
N _b : Biaxial nematic phase	BP: Blue phase
N _D : Discotic nematic phase	Sm: Smectic phase
SmA: Smectic-A phase	SmC: Smectic-C phase
Iso: Isotropic phase	SmC*: Chiral smectic-C phase
o-ray: Ordinary ray	e-ray: Extraordinary ray
Δn : Birefringence	n_e : Extraordinary refractive index
$\hat{n}$: Director unit vector	n_o : Ordinary refractive index

P : Polarization	P_f : Flexoelectric polarization
$\vec{r}$: Rubbing direction	E_{gap} : Energy band-gap
K_{11} : Splay elastic constant	K_{22} : Twist elastic constant
K_{33} : Bend elastic constant	V_{PP} : Peak-to-peak voltage
ϵ_0 : Free-space permittivity	ϵ^* : Complex dielectric permittivity
ϵ' : Real part of ϵ^*	ϵ'' : Imaginary part of ϵ^*
$\Delta\epsilon$: Dielectric anisotropy	ϵ_∞ : High-frequency limit of permittivity
$\delta\epsilon$: Dielectric strength	$\tan \delta$: Dielectric loss factor
μ : Dipole moment	f_R : Relaxation frequency
S : Orientational order parameter	V_{th} : Threshold voltage
T^{**} : Nematic superheating temperature	P_S : Saturation polarization
σ_{ac} : AC conductivity	T^* : Isotropic supercooling temperature
γ : Coupling parameter	τ_P : Polarization switching time
E_a : Activation energy	σ_{dc} : DC conductivity
k_B : Boltzmann constant	N_c : Number of molecules in a cluster
E_{int} : Interaction energy	
FESEM: Field emission scanning electron microscopy	
HOMO: Highest occupied molecular orbital	
LUMO: Lowest unoccupied molecular orbital	
FTIR: Fourier transform infrared spectroscopy	
Cryo-TEM: Cryo transmission electron microscopy	