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Original Research Article

Optical Properties of Liquid Crystals in Biosensing Applications

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Abstract

Introduction: Liquid crystals (LCs) combine fluidity with long-range molecular order, giving rise to strong optical anisotropy (birefringence), polarization-dependent transmission, and (in cholesterics) selective reflection. These features make LC interfaces exquisitely sensitive to biomolecular binding events that perturb anchoring and director fields, enabling label-free biosensing.

Materials and Methods: A structured literature review (2016–Jan 2026) was designed around optical LC biosensors (nematic, cholesteric, blue phase, chromonic; planar films, droplets, elastomers, microcavities). Studies were screened using predefined inclusion/exclusion criteria and extracted for platform geometry, surface chemistry, optical readout, target class, and analytical performance.

Results: Across included studies, dominant readouts were polarized optical microscopy (POM) texture change, quantitative birefringence/retardation, and wavelength shifts from cholesteric reflection bands. Sensitivity improvements were commonly achieved via nucleic-acid amplification strategies and signal-amplifying interfacial chemistries. Six synthesis tables summarize optical properties, device architectures, functionalization routes, readout metrics, representative targets, and translation considerations.

Conclusion: LC optical biosensors are maturing from qualitative "dark-to-bright" assays toward quantitative, portable formats using smartphone optics, elastomeric photonic films, and robust surface chemistries. Key remaining challenges include standardization of alignment layers, suppression of matrix effects in biofluids, and reproducible quantification across lighting/imaging conditions.

Keywords: liquid crystal; birefringence; cholesteric reflection; polarized optical microscopy; label-free biosensor; surface anchoring; point-of-care.

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Introduction

Liquid crystals (LCs) occupy an intermediate state of matter between crystalline solids and isotropic liquids, characterized by molecular mobility coupled with orientational order. This order makes LCs optically anisotropic: light propagating through an LC experiences different refractive indices depending on polarization and propagation direction, producing birefringence and retardation that can be visualized by crossed polarizers. In biosensing, this optical amplification is harnessed by translating nanoscale biochemical interactions at an interface into microscale reorientation of the LC director field—an effect that is readily observed as texture changes under polarized optical microscopy (POM). [1-3]

Most LC biosensors rely on changes in surface anchoring. When a glass substrate is modified with a homeotropic alignment agent (e.g., silane/surfactant layers), a nematic LC film can appear uniformly dark under crossed polarizers because the director is normal to the substrate. Binding of biomolecules (proteins, nucleic acids, lipids, cells, toxins) at the interface introduces roughness, charge, and heterogeneous wettability, weakening or locally breaking anchoring and forcing a transition toward planar or tilted alignment—yielding bright textures and defect patterns. [2,4,5] This makes the LC interface an "optical transducer" for interfacial chemistry, enabling label-free detection.

Beyond nematic films, recent work has expanded to (i) LC droplets and droplet-in-hydrogel formats, where confinement creates defect structures that respond strongly to interfacial binding, [6,7] (ii) cholesteric LCs (ChLCs), which possess a helical structure producing selective reflection (structural color) that shifts with pitch changes and surface perturbations, [8,9] and (iii) blue phase LCs, which

offer three-dimensional cubic defect networks and can support sensitive optical responses without traditional alignment layers. [10] Quantification is evolving from qualitative texture inspection to measurable optical metrics: transmitted intensity (RGB or grayscale) under standardized illumination, birefringence/retardation mapping, and reflection-peak wavelength shifts for cholesterics. [3,8,11] Integrating LCs with microfluidics has improved sample handling, reduced consumption, and enabled multiplexing, while coupling to biochemical amplification (e.g., rolling circle amplification) has pushed detection limits into clinically relevant ranges. [12,13] At the same time, the field is moving toward portability: smartphone-based polarization imaging and low-cost optical hardware are increasingly used to reduce operator dependence and improve reproducibility. [14,15]

This article reviews how LC optical properties—birefringence, polarization-dependent scattering/transmission, defect-mediated textures, and cholesteric photonic reflection—are exploited in biosensing, emphasizing material choices, device geometries, and the methods used to convert optical patterns into quantitative analytical signals. We synthesize performance trends, highlight design rules for robust sensing in complex matrices, and outline challenges for translation to point-of-care and field settings. [2,3,15]

Materials and Methods

A structured literature review was performed to summarize optical LC biosensing platforms and relate analytical performance to LC optical properties and interfacial mechanisms.

Data sources and search strategy: Searches were performed across major scholarly databases (e.g., PubMed, Web of Science/Scopus, and publisher platforms) for the period January 1, 2016 to January 26, 2026 using combinations of: “liquid crystal biosensor”, “nematic”, “cholesteric”, “blue phase”, “chromonic”, “birefringence”, “polarized optical microscopy”, “reflection band”, “photonic”, “droplet”, “aptamer”, “immunoassay”, “point-of-care”, “smartphone”.

Inclusion criteria

Studies were included if they met **all** of the following:

1. **LC-based transducer**: Used thermotropic nematic/blue-phase/cholesteric LCs, LC droplets, LC elastomers, or lyotropic chromonic LCs as the signal-transduction medium.
2. **Optical readout**: Reported an optical measurement (POM textures/intensity, birefringence/retardation, reflection wavelength/colorimetry, optical microcavity output, or related photonic signal).
3. **Biosensing target**: Detected a biological analyte (proteins, nucleic acids, biomarkers, pathogens, metabolites), or biologically relevant toxins/antibiotics with explicit biosensing claims.
4. **Method transparency**: Provided sufficient experimental details to identify LC material/phase, surface functionalization, and readout method.
5. **Publication type and date**: Peer-reviewed journal articles or substantial reviews published 2016 or later.

Exclusion criteria: Studies were excluded if they met any of the following:

1. Non-optical-only outputs (purely electrical/impedance with no LC optical quantification).
2. LC papers focused solely on displays/photonic devices without a sensing application.
3. Non-biological chemical sensing without a biosensing context (unless demonstrated in biological matrices or framed as a biosensor).
4. Conference abstracts lacking full methods/results, theses, or non-peer-reviewed reports.
5. Articles prior to 2016.

Study selection: Titles/abstracts were screened first, followed by full-text assessment against criteria. Disagreements (if any) were resolved by applying stricter adherence to inclusion items 1–3 (LC transducer + optical readout + biosensing target).

Data extraction and synthesis

From each included study, the following were extracted: LC phase/material (e.g., 5CB, cholesteric mixtures, chromonic dyes), geometry (film/droplet/elastomer/microcavity), alignment layer (e.g., silanes/surfactants/polymers), biorecognition element (antibody, aptamer, DNA probe), sample matrix (buffer/serum/blood), optical modality (POM, reflection spectroscopy, smartphone imaging), and performance descriptors (dynamic range, response time, qualitative/quantitative nature). Findings were synthesized narratively and summarized in six tables.

Results

Table 1: LC Phases and Optical Properties Leveraged For Biosensing

LC class	Key optical property	What changes upon binding	Typical observable
Nematic films	Birefringence/retardation	Anchoring tilt + director distortion	Dark→bright under crossed polars; texture/defects
LC droplets	Defect topology (boojums/hedgehogs) + birefringence	Interfacial ordering + defect relocation	Texture class shift; intensity redistribution
Cholesteric	Selective reflection (Bragg band)	Pitch/effective refractive index changes	Color shift; reflection-peak wavelength shift
Blue phase	3D defect lattice; polarization response	Defect network perturbation	Strong texture/color change without strict alignment
Chromonic (lyotropic)	Anisotropic absorbance/birefringence	Assembly/orientation at interface	POM texture + (sometimes) electrical/optical hybrid

Nematic systems dominate because small anchoring perturbations yield large birefringence changes; cholesterics offer "built-in colorimetry" for field use; droplets provide intrinsic amplification through defect energetics and confinement. [2,3,8]

Table 2:Device Geometries Used In Optical Lc Biosensing

Geometry	Interface engineered	Strengths	Typical limitations
Planar LC cell (glass–LC–glass)	Solid alignment layer + aqueous interface	Simple, inexpensive; compatible with POM	Sensitive to dust, illumination variability
Open LC interface (LC–aqueous)	Surfactant/lipid/functional layer	Direct biomolecule access; fast response	Evaporation, flow disturbances
Droplet-in-water	Droplet surface functionalization	High sensitivity; small sample volume	Droplet size polydispersity affects readout
Droplet-in-hydrogel sheet	Hydrogel matrix + droplet interfaces	Portable handling; multiplexing potential	Diffusion-limited response for large proteins
Cholesteric films/elastomers	Photonic helix / CLCE films	Colorimetric, camera-readable output	Mechanical strain/temperature can confound
Microfluidic LC chips	Channel walls + LC regions	Automation; multiplexing; low volume	Fabrication complexity; alignment reproducibility

Architecture selection is largely a tradeoff between robustness and sensitivity. Microfluidics and hydrogel sheets improve handling and portability, while cholesteric photonic formats improve naked-eye/phone readability. [6,7,14]

Table 3: Surface functionalization and biorecognition strategies

Recognition element	How it couples to LC optics	Example benefit	Common pitfalls
Antibodies (immunosensors)	Mass/roughness + charge changes at interface	High specificity in clinical targets	Orientation control needed; nonspecific adsorption
Aptamers	Conformation change + target binding triggers anchoring disruption	Stable, synthetic, tunable	Salt dependence; matrix effects in serum
DNA probes (hybridization)	Surface-bound duplex formation perturbs anchoring	Sequence specificity	Hybridization kinetics, temperature sensitivity
Enzymes/metabolite schemes	Reaction products change pH/ionic strength affecting alignment	Metabolite sensing (e.g., cholesterol/glucose proxies)	Cross-reactivity; buffer dependence
Amplification (RCA/HCR, etc.)	Large nucleic-acid products strongly disrupt LC ordering	Orders-of-magnitude sensitivity gain	Added steps; contamination risk

The most reliable quantitative gains come from producing "big" interfacial perturbations (e.g., amplified DNA products) that overpower background noise from alignment layers and imaging variability. [12,13]

Table 4: Optical readout modalities and quantitative metrics

Readout	Measurement	Quantification approach	Suitable for POC?
POM texture	Polarization-dependent transmission	Intensity histograms, texture classifiers	Moderate (needs polarizers/camera)
Retardation mapping	Phase delay (Δn·d)	Birefringence calibration vs. analyte	Moderate–high (needs stable optics)
Cholesteric reflection	Peak wavelength / RGB color	Wavelength shift or RGB→concentration model	High (phone camera + calibration card)
Smartphone polarized imaging	RGB or grayscale under polarizers	App-based segmentation + standard lighting	High
Photonic/microcavity coupling	Spectral output change	Peak shift, threshold change	Moderate (more complex instrumentation)

POM remains the workhorse but is operator-dependent; phone-based standardized imaging and cholesteric wavelength/color readouts are best positioned for translation because they reduce microscope dependence. [14,15]

Table 5: Representative post-2015 LC optical biosensing demonstrations (examples)

Target class	Example target	LC format	Signal type	Notable approach
Proteins	Serum albumin / model proteins	Blue phase / nematic	Texture/intensity change	Alignment-layer-light or blue-phase sensitivity [10]
Cancer biomarkers	PDGF-BB, adenosine	Nematic + amplification	Dark→bright after RCA	Magnetic enrichment + RCA boosts [12]
Antibiotics	Amoxicillin	Nematic film	Texture change	Aptamer probe on mixed alignment layer [5]
Growth factors	IGF-I	Nematic	Birefringence immunoassay	Quantitative birefringence readout[11]
Pathogens	E. coli (example)	Portable optical platform	Image-based quantification	Low-cost optical prototype + pixel analysis [14]
Metabolites/toxins	Cholesterol, malathion	Cholesteric elastomer	Colorimetric reflection	Portable structural color sensing [16]

Clinical translation is strongest where (a) the target–receptor chemistry creates large interfacial changes, and (b) the optical output is inherently quantitative (reflection peaks or calibrated image metrics). [11,12,16]

Table 6: Translation considerations for LC optical biosensors

Issue	Why it matters	Practical mitigation
Matrix effects (serum/blood)	Proteins/salts disrupt anchoring nonspecifically	Blocking layers, magnetic enrichment, dilution protocols
Temperature sensitivity	LC phase/viscosity and cholesteric pitch drift	Thermal control or internal reference calibration
Illumination variability	Alters intensity metrics and colorimetry	Fixed light source + calibration card/standards
Alignment-layer aging	Drift in homeotropic strength and noise floor	Shelf-life testing; robust silane chemistry
Reproducibility across devices	Limits multi-site comparability	Standardized cell gap, imaging geometry, QA textures
Automation	Needed for workflow and throughput	Microfluidics, cartridges, app-based analysis

The main barriers are not “can it sense?”, but “can it sense reproducibly in real samples with minimal user steps?”. Approaches such as enrichment, amplification, and controlled imaging are repeatedly used to address this. [12,14,15]

Discussion

The reviewed literature shows a clear mechanistic thread: LC optical signals are governed by how biomolecular events perturb anchoring energy and elastic distortion, which then control birefringence and defect textures observed under polarization. Reviews from 2021–2024 emphasize that, while

the transduction physics is well understood, practical performance depends strongly on surface chemistry and readout standardization. [2,3,17] In nematic film sensors, the most common "dark-to-bright" transition is powerful but vulnerable to false positives from nonspecific adsorption and subtle changes in surfactant organization. This has motivated methods that either (i) generate larger interfacial perturbations than background noise or (ii) use inherently quantitative photonic outputs.

Signal amplification strategies illustrate (i). For example, rolling circle amplification coupled to LC readout produced large DNA products that strongly disrupt LC ordering, enabling sensitive biomarker detection even in blood matrices by reducing direct matrix–LC contact via magnetic bead enrichment. [12] Similar logic underpins split-aptamer designs and nucleic-acid chain reactions, which translate binding into amplified interfacial mass/charge and stronger optical disruption. [13,18]

These approaches shift LC biosensing closer to molecular diagnostics while retaining label-free optical transduction at the final step.

Cholesteric systems illustrate (ii). Because cholesterics selectively reflect a wavelength band determined by pitch and refractive indices, binding-induced changes can be encoded as a color shift measurable by simple cameras. Recent cholesteric elastomer demonstrations show that portable, quantitative sensing is feasible when mechanical/thermal confounders are controlled or calibrated. [16] This aligns with broader trends toward camera-readable biosensors, where the "instrument" becomes a smartphone and the key innovation is robust image normalization rather than complex optics.

Droplet-based LC biosensors remain attractive because confinement and defects amplify sensitivity. Droplet-in-hydrogel sheets combine portability with multiplexing potential by physically separating sensing elements and enabling easy handling. [6] Yet droplet polydispersity and imaging variability can broaden signals; thus, microfluidic droplet generation and automated classification are increasingly important. Additionally, droplet systems can be more tolerant of imperfect alignment layers than planar cells, which may aid real-world deployment.

Comparing with prior studies, the field has moved from proof-of-concept texture changes toward quantitative frameworks: birefringence immunoassays, standardized imaging pipelines, and low-cost hardware platforms. [11,14,15]

The most promising near-term direction is likely hybridization of (a) robust surface chemistry (antifouling + oriented capture probes), (b) controlled microfluidic or cartridge formats, and (c) phone-based analysis with internal optical standards. In parallel, coupling LCs to photonic structures (microcavities, structured reflectors) may further enhance sensitivity, but the added instrumentation must be justified by clinical value and workflow simplicity. [3,17] Overall, LC biosensing is transitioning into an engineering discipline: performance now depends less on demonstrating optical response and more on controlling variability—surface aging, sample matrices, temperature, and imaging conditions—so that LC optical properties become a dependable quantitative readout rather than a qualitative effect. [2,15,17]

Conclusion

Liquid crystals provide a unique optical amplification mechanism for biosensing: molecular binding events at interfaces translate into large, visible changes in birefringence, defect textures, or cholesteric structural color. Post-2015 advances show a shift toward quantitative readouts (birefringence mapping and reflection-peak analysis), higher sensitivity via biochemical amplification, and improved portability through low-cost optics and smartphone analysis. Remaining priorities for translation include antifouling surface chemistries for complex biofluids, standardized illumination and imaging pipelines, and manufacturable device architectures (microfluidic cartridges, hydrogel sheets, and photonic films) that deliver reproducible results across settings.

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