DEVELOPMENT OF LIQUID CRYSTAL BASED DEVICES FOR OPTICAL AND SOLAR ENERGY HARVESTING APPLICATIONS

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by

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Submitted

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Dedicated to my Parents and Supervisor

CERTIFICATE

This is to certify that the thesis entitled ***"Development of Liquid Crystal based Devices for Optical and Solar Energy Harvesting Applications,"*** being submitted by **Mr. Vaibhav Sharma** 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 submitting 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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Vaibhav Sharma

ABSTRACT

Optical devices are instruments or components that manipulate light in various ways to perform specific functions. They are fundamental in many technologies and applications, particularly those involving the transmission, modulation, or detection of light. Once fabricated, these devices are challenging to tune or reconfigure across a wide wavelength range. However, the next generation of optical devices requires dynamic reconfigurability, cost-effectiveness, and power efficiency. These capabilities can be achieved over a limited dynamic range using thermo-optic or electro-optic materials. Liquid crystals (LCs), with their high birefringence, significant electro-optic effect, and low power consumption, offer a promising solution for developing electrically tunable optical devices with a wide dynamic range. This thesis focuses on utilizing LC materials in switchable optical devices, targeting the application in the fields of optics, photonics, and solar energy harvesting.

The first two chapters of the thesis cover the fundamental concepts and properties of LCs, optical waveguides, surface plasmon resonance (SPR), and photoluminescence (PL), as well as the experimental methods and techniques used in the research. In chapters 3 and 4, we used the 5CB nematic LC in the waveguide configuration to design and fabricate the mode size converter, optical switch, and polarization selector. One of the key advantages of using LC as the core material for creating a liquid crystal core waveguide (LCW) is the capability to adjust the propagation characteristics of guided-wave devices based on LCWs. In Chapter 3, we present the numerical and experimental study of an LC core periodically segmented waveguide (PSW) based mode size converter fabricated on an ITO-coated glass substrate. Here, we have shown that the effective index and mode size of the guided modes change with the duty cycle and the applied voltage. For a fixed duty cycle, we have experimentally demonstrated that the size of the fundamental mode can be tuned by the applied voltage. The advantage of using LC-PSW for mode size transformation is that the effective index and mode size in the fabricated waveguide can be varied by an externally applied electric field. In this work, we have also experimentally demonstrated that the appropriate choice of the applied voltage can maximize the coupling efficiency between the LC-PSW and single-mode fiber. The proposed mode size converter can be used in LC photonic lightwave circuits to couple the light between optical devices with maximum efficiency. To improve the performance of LCWs in terms of threshold voltage, extinction ratio, and insertion loss, we have successfully designed, fabricated, and characterized rectangular-core channel LCWs with a cross-section of 10 μm × 5 μm (width × height) in Chapter 4. Our experimental results demonstrate that the device works as a low-voltage-controlled optical

switch. The device offers several advantages, including easy integration with optical fiber pigtails, low insertion losses, low power dissipation, and electrical tunability. The fabricated device is further demonstrated as a voltage-controlled polarization selector that passes either TM or TE-polarized light with a polarization extinction ratio of 28 dB and 25 dB, respectively.

In Chapter 5, we focused on fabricating an active polarization beam splitter (PBS) by sandwiching the 6CHBT nematic LC between the two prisms. Polarization handling using an external source is highly desirable in applied optics and photonics to increase the degree of freedom of an optical system. Here, an electrically controlled LC-PBS is presented that can operate in two different modes: non-splitting mode and polarization splitting mode. The externally applied voltage can switch the mode of the PBS, which makes the device active and flexible. The presented electrically controlled PBS exhibits features such as bistability with highly stable modes, large splitting angle, wider operating range, and ease of fabrication with lower cost. Chapter 6 investigates the method to detect the purity of an LC material using the SPR phenomena. The development of LC-based technology is happening at a quick pace in the design of various switchable optical devices due to the exceptional electro-optical properties of LCs. The purity of an LC is the primary concern for these applications. In this chapter, we present a straightforward and effective optical method to detect the purity of an LC using SPR phenomena. The Kretschmann configuration is used in the proposed technique, and an LC cavity is formed over the metal layer using a glass substrate. Various impurities are added in the pure LC, which disturbs the molecular arrangement of the LC molecules, and hence, the refractive index of LC changes. We have numerically calculated and experimentally observed the shift in the resonance angle for the impure LC as compared to the pure one. The experimentally measured sensitivity of the proposed technique is around 150°/ RIU, which is comparable to the other Kretschmann configuration-based sensors. Compared to the existing LC purity detection method, the key advantages of the proposed method are its lightweight, compact design, label-free detection, and real-time monitoring capabilities.

In Chapter 7, we attempt to explore solar energy harvesting applications and discuss the possibilities of using LC to design and fabricate a highly efficient luminescent solar concentrator (LSC). LSC combined with photovoltaic cells is in high demand, and it is a very effective way to increase the efficiency of a commercially available silicon solar panel. This is a promising solution for building integrated photovoltaics (BIPV) and could be a highly important element of our daily life for solar energy harvesting. Despite having high potential, the optical efficiencies of the currently available LSCs are not very high. In this Chapter, we present a scattering enhanced optical efficiency of an LSC by incorporating a polymer-stabilized cholesteric liquid crystal with a high fluorescence organic dye between the two glass substrates. In the waveguiding layer, the chiral nematic director of LC exhibits random orientation; hence, a scattering is observed in the film. These scattering elements increase the probability of light absorption of the dye in the ultraviolet region and subsequently enhance the re-emission of the light in the visible region. Moreover, the material shows a large Stokes shift and a very low overlap between the absorption and emission spectra. We have achieved a high optical efficiency of 37 %, along with a concentration factor of more than 4.5 for the fabricated LSC. A Monte Carlo simulation is also developed to calculate the efficiency of the proposed device theoretically, and it shows good agreement with the experimental results. These findings create opportunities for developing highly efficient LSC windows capable of generating power for BIPV applications. In the end, chapter 8 concludes the detailed work of all the chapters presented in the thesis. The potential applications and future scope of the proposed LC-based devices for next-generation optics, photonics, and solar energy harvesting are also described in this chapter.

सारांश

ऑप्टिकल डिवाइस वे उपकरण या घटक होते हैं जो प्रकाश को विभिन्न तरीकों से नियंत्रित करते हैं ताकि विशिष्ट कार्यों को पूरा किया जा सके। वे उन प्रौद्योगिकियों और अनुप्रयोगों में मौलिक होते हैं, विशेष रूप से जो प्रकाश के संचरण, माडुलन, या पहचान से संबंधित होते हैं। एक बार बनाए जाने के बाद, इन उपकरणों को व्यापक तरंग दैर्ध्य सीमा में समायोजित या पुन: कॉन्फ़िगर करना चुनौतीपूर्ण होता है। हालांकि, अगली पीढ़ी के ऑप्टिकल उपकरणों को गतिशील पुन: कॉन्फ़िगर करने की क्षमता, लागत-प्रभावशीलता, और ऊर्जा दक्षता की आवश्यकता होगी। इन क्षमताओं को सीमित गतिशील सीमा के भीतर थर्मो-ऑप्टिक या इलेक्ट्रो-ऑप्टिक सामग्री का उपयोग करके प्राप्त किया जा सकता है। लिक्विड क्रिस्टल्स (एलसी), अपने उच्च द्विआध्रुवीयता, महत्वपूर्ण इलेक्ट्रो-ऑप्टिक प्रभाव और कम ऊर्जा खपत के साथ, व्यापक गतिशील सीमा के साथ विद्युत रूप से ट्यून करने योग्य ऑप्टिकल उपकरणों के विकास के लिए एक आशाजनक समाधान प्रस्तुत करते हैं। यह थीसिस एलसी सामग्री का उपयोग करके स्विच करने योग्य ऑप्टिकल उपकरणों को विकसित करने पर केंद्रित है, जिसका लक्ष्य ऑप्टिक्स, फोटोनिक्स और सौर ऊर्जा संग्रहण के क्षेत्रों में अनुप्रयोग है।

थीसिस के पहले दो अध्यायों में एलसी, ऑप्टिकल वेवगाइड्स, सतह प्लाज्मन अनुनाद (एसपीआर), और फोटोलुमिनेसेंस के मौलिक अवधारणाओं और गुणों, साथ ही अनुसंधान में प्रयुक्त प्रायोगिक तरीकों और तकनीकों को शामिल किया गया है। अध्याय तीन और चार में, हमने वेवगाइड कॉन्फ़िगरेशन में 5CB नेमेटिक एलसी का उपयोग करके मोड साइज कन्वर्टर, ऑप्टिकल स्विच, और ध्रुवीकरण चयनकर्ता को डिज़ाइन और निर्मित किया है। एक एलसी कोर वेवगाइड (एलसीडब्ल्यू) बनाने के लिए एलसी का कोर सामग्री के रूप में उपयोग करने के मुख्य लाभों में से एक यह है कि एलसीडब्ल्यू आधारित गाइडेड-वेव उपकरणों की संचरण विशेषताओं को समायोजित किया जा सकता है। अध्याय तीन में, हम ITO-लेपित ग्लास सब्सट्रेट पर निर्मित एक एलसी कोर समय-समय पर खंडित वेवगाइड (पीएसडब्ल्यू) आधारित मोड साइज कन्वर्टर का संख्यात्मक और प्रायोगिक अध्ययन प्रस्तुत करते हैं। यहां, हमने दिखाया है कि ड्यूटी साइकिल और लागू वोल्टेज के साथ गाइडेड मोड्स के प्रभावी सूचकांक और मोड साइज बदलते हैं। एक निश्चित ड्यूटी साइकिल के लिए, हमने प्रायोगिक रूप से यह प्रदर्शित किया है कि मूलभूत मोड का आकार लागू वोल्टेज द्वारा समायोजित किया जा सकता है। मोड साइज परिवर्तन के लिए एलसी - पीएसडब्ल्यू का उपयोग करने का लाभ यह है कि निर्मित वेवगाइड में प्रभावी सूचकांक और मोड साइज को बाहरी रूप से लागू विद्युत क्षेत्र द्वारा बदला जा सकता है। इस कार्य में, हमने यह भी प्रायोगिक रूप से प्रदर्शित किया है कि उचित वोल्टेज चयन एलसी - पीएसडब्ल्यू और सिंगल-मोड फाइबर के बीच युग्मन दक्षता को अधिकतम कर सकता है। प्रस्तावित मोड साइज कन्वर्टर को एलसी फोटोनिक लाइटवेव सर्किट्स में ऑप्टिकल उपकरणों के बीच प्रकाश को अधिकतम दक्षता के साथ

जोड़ने के लिए उपयोग किया जा सकता है। एलसीडब्ल्यू के प्रदर्शन में सुधार करने के लिए, थ्रेशहोल्ड वोल्टेज, एक्सटिंक्शन अनुपात, और इंसर्शन लॉस के संदर्भ में, हमने अध्याय 4 में 10 μm × 5 μm (चौड़ाई × ऊंचाई) के क्रॉस-सेक्शन के साथ आयताकार-कोर चैनल एलसीडब्ल्यू को सफलतापूर्वक डिज़ाइन, निर्मित और विशेषता की है। हमारे प्रायोगिक परिणाम बताते हैं कि उपकरण एक कम-वोल्टेज नियंत्रित ऑप्टिकल स्विच के रूप में कार्य करता है। उपकरण कई लाभ प्रदान करता है, जिसमें ऑप्टिकल फाइबर पिगटेल्स के साथ आसान एकीकरण, कम इंसर्शन लॉस, कम ऊर्जा खपत, और विद्युत नियंत्रित करने की क्षमता शामिल है। निर्मित उपकरण को आगे एक वोल्टेज-नियंत्रित ध्रुवीकरण चयनकर्ता के रूप में प्रदर्शित किया गया है, जो या तो TM या TE ध्रुवीकृत प्रकाश को ध्रुवीकरण एक्सटिंक्शन अनुपात 28 dB और 25 dB के साथ पास करता है।

अध्याय 5 में, हमने दो प्रिज्मों के बीच 6CHBT नेमेटिक एलसी को सैंडविच करके एक सक्रिय ध्रुवीकरण बीम विभाजक (पीबीएस) के निर्माण पर ध्यान केंद्रित किया है। बाहरी स्रोत का उपयोग करके ध्रुवीकरण को नियंत्रित करना अनुप्रयुक्त ऑप्टिक्स और फोटोनिक्स में अत्यधिक वांछनीय है ताकि ऑप्टिकल प्रणाली की स्वतंत्रता की डिग्री बढ़ाई जा सके। यहां, एक विद्युत रूप से नियंत्रित एलसी -PBS प्रस्तुत किया गया है जो दो अलग-अलग मोड में काम कर सकता है: गैर-विभाजन मोड और ध्रुवीकरण विभाजन मोड। बाहरी रूप से लागू वोल्टेज पीबीएस के मोड को स्विच कर सकता है, जो उपकरण को सक्रिय और लचीला बनाता है। प्रस्तुत विद्युत रूप से नियंत्रित पीबीएस में द्विस्थिरता जैसी विशेषताएं हैं, जिसमें अत्यधिक स्थिर मोड, बड़ा विभाजन कोण, व्यापक ऑपरेटिंग सीमा, और कम लागत के साथ आसानी से निर्माण किया जा सकता है।

अध्याय 6 में, हम एसपीआर घटना का उपयोग करके एलसी सामग्री की शुद्धता का पता लगाने के तरीके की जांच करते हैं। एलसी की असाधारण इलेक्ट्रो-ऑप्टिकल गुणों के कारण विभिन्न स्विच करने योग्य ऑप्टिकल उपकरणों के डिजाइन में एलसी -आधारित प्रौद्योगिकी का तेजी से विकास हो रहा है। इन अनुप्रयोगों के लिए एलसी की शुद्धता प्रमुख चिंता का विषय है। इस अध्याय में, हम एसपीआर घटना का उपयोग करके एलसी की शुद्धता का पता लगाने के लिए एक सरल और प्रभावी ऑप्टिकल विधि प्रस्तुत करते हैं। प्रस्तावित तकनीक में क्रेट्स्चमैन कॉन्फ़िगरेशन का उपयोग किया गया है, और एक कांच के सब्सट्रेट का उपयोग करके धातु की परत पर एक एलसी कैविटी बनाई गई है। शुद्ध एलसी में विभिन्न अशुद्धियाँ जोड़ी गई हैं, जो एलसी अणुओं की आणविक व्यवस्था को बाधित करती हैं, और इसलिए, एलसी का अपवर्तनांक बदलता है। हमने संख्यात्मक रूप से गणना की है और प्रायोगिक रूप से देखा है कि शुद्ध एलसी की तुलना में अशुद्ध एलसी के लिए अनुनाद कोण में परिवर्तन होता है। प्रस्तावित तकनीक की प्रायोगिक रूप से मापी गई संवेदनशीलता लगभग 150^0/RIU है, जो अन्य क्रेट्स्चमैन कॉन्फ़िगरेशन-आधारित सेंसरों के तुलनीय है। मौजूदा एलसी शुद्धता पहचान विधि की तुलना में, प्रस्तावित विधि के प्रमुख लाभ इसके हल्के, कॉम्पैक्ट डिजाइन, लेबल-मुक्त पहचान, और वास्तविक समय की निगरानी क्षमताएं हैं।

अध्याय 7 में, हम सौर ऊर्जा संग्रहण अनुप्रयोगों का पता लगाने का प्रयास करते हैं और एलसी का उपयोग करके एक अत्यधिक कुशल लुमिनेसेंट सौर कंसन्ट्रेटर (एलएससी) को डिजाइन और निर्मित करने की संभावनाओं पर चर्चा करते हैं। एलएससी को फोटोग्राफिक सेल के साथ जोड़ना अत्यधिक मांग में है, और यह एक व्यावसायिक रूप से उपलब्ध सिलिकॉन सोलर पैनल की दक्षता बढ़ाने का एक बहुत प्रभावी तरीका है। यह भवन एकीकृत फोटोग्राफिक्स के लिए एक आशाजनक समाधान है और सौर ऊर्जा संग्रहण के लिए हमारे दैनिक जीवन का एक अत्यधिक महत्वपूर्ण तत्व हो सकता है। उच्च क्षमता होने के बावजूद, वर्तमान में उपलब्ध एलएससी की ऑप्टिकल दक्षताएं बहुत अधिक नहीं हैं। इस अध्याय में, पहली बार (हमारे ज्ञान के अनुसार), हम एक बहुलक-स्थिर कोलेस्टेरिक लिक्विड क्रिस्टल को उच्च फ्लोरोसेंट ऑर्गेनिक डाई के साथ दो-ग्लास सब्सट्रेट के बीच शामिल करके एलएससी की ऑप्टिकल दक्षता में वृद्धि प्रस्तुत करते हैं। तरंगमार्गीय परत में, एलसी का चिरल नेमेटिक निदेशक यादृच्छिक अभिविन्यास प्रदर्शित करता है; इसलिए, फिल्म में एक प्रकीर्णन देखा जाता है। इन प्रकीर्णन तत्वों से अल्ट्रावायलेट क्षेत्र में डाई द्वारा प्रकाश अवशोषण की संभावना बढ़ जाती है और इसके परिणामस्वरूप दृश्य क्षेत्र में प्रकाश के पुनः उत्सर्जन में वृद्धि होती है। इसके अलावा, इस सामग्री में बड़ा स्टोक्स शिफ्ट और अवशोषण तथा उत्सर्जन स्पेक्ट्रा के बीच बहुत कम ओवरलैप होता है। हमने निर्मित एलएससी के लिए 37% की उच्च ऑप्टिकल दक्षता और 4.5 से अधिक का संकेंद्रण कारक हासिल किया है। प्रस्तावित डिवाइस की दक्षता की सैद्धांतिक रूप से गणना करने के लिए एक मोंटे कार्लो सिमुलेशन भी विकसित किया गया है, और यह प्रयोगात्मक परिणामों के साथ अच्छी संगति दिखाता है। ये निष्कर्ष अत्यधिक कुशल एलएससी खिड़कियों के विकास के अवसर पैदा करते हैं जो बीआईपीवी अनुप्रयोगों के लिए ऊर्जा उत्पन्न करने में सक्षम हैं। अंत में, अध्याय 8 में थीसिस में प्रस्तुत सभी अध्यायों के विस्तृत कार्य का निष्कर्ष प्रस्तुत किया गया है। अगली पीढ़ी के ऑप्टिक्स, फोटोनिक्स और सौर ऊर्जा संचयन के लिए प्रस्तावित एलसी -आधारित उपकरणों के संभावित अनुप्रयोगों और भविष्य के विस्तार का भी इस अध्याय में वर्णन किया गया है।

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LIST OF SYMBOLS AND ABBREVIATIONS

LC: Liquid crystal

LCD: Liquid crystal display

PBS: Polarization beam splitter

SPR: Surface plasmon resonance

LSC: Luminescent solar concentrator

PV: Photovoltaic

LCPC: Liquid crystal polymer composite

UV: Ultraviolet

PL: Photoluminescence

POM: Polarizing optical microscopy

PSW: Periodically segmented waveguide

ITO: Indium tin oxide

NSM: Non splitting mode

PSM: Polarization splitting mode

TE: Transverse electric

TM: Transverse magnetic

CLC: Cholesteric liquid crystal

PSCLC: Polymer-stabilized cholesteric liquid crystal

TIR: Total internal reflection

IL: Insertion loss

BIPV: Building integrated photovoltaics

EDF: Extra dense flint

S: Vertical polarization

P: Horizontal polarization

PER: Polarization extinction ratio

CTAB: Cetyltrimethylammonium bromide

NOA65: Norland optical adhesive- 65

SP: Surace plasmon

SPP: Surface plasmon polariton

IPS: In plane switching

QY: Quantum yield

5CB: 4-cyano-4′-pentylbiphenyl

6CHBT: 4-(trans-4-n-hexylcyclohexyl) isothiocyanatobenzene

E7: 4-cyano-4′-octyl biphenyl

CB15: (4'-[(S)-2-Methylbutyl] biphenyl-4-carbonitrile),

$\Delta\varepsilon$: Dielectric Anisotropy

ε_{II} : Dielectric permittivity along long axis of LC

$\varepsilon_{\perp}$: Dielectric permittivity along short axis of LC

V_{sat} : Saturation voltage

γ_{rv} : Rotational viscosity

θ: Orientational angle of LC

Δn: Optical birefringence

n_e: Extraordinary refractive index

n_o: Ordinary refractive index

$\hat{n}$: Liquid crystal director

K_{11}: Splay elastic constant

K_{22}: Twist elastic constant

K_{33}: Bend elastic constant

ε_o: Free space permittivity

V_{th}: Threshold voltage

V_{ft}: Freedericksz transition voltage

V_a: Applied voltage

E_{ft}: Freedericksz transition field

S: Sensitivity

SMF: Single-mode fiber

k_{sp}: Propagation constant of the SP wave

ε_m : Dielectric permittivity of metal

n_{eff}: Effective refractive index

n_{core}: Refractive index of the core

n_{cl}: Refractive index of the cladding

n_{eqv}: Equivalent Refractive index of the core

V: Normalized frequency

n_p: Refractive index of the prism

η_{opt}: Optical Efficiency

FF: Fill factor

C: Concentration factor

b: Normalized propagation constant

$T_{Cr\text{-}N}$: Melting point

$T_{N\text{-}I}$: Clearing point

Q: Order parameter

DI: Deionized