

# Random Formation of Twelve Types of Liquid Crystal Micropatterns for Unclonable Optical Security

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## ABSTRACT

An optical PUF is realized by spin coating nematic liquid crystal onto glass Micropatterns and thermally inducing phase transition. Channel width control (0–9 μm) yields twelve distinct director patterns under competing anchoring. Polarized microscopy captures unique, reproducible fingerprints. This simple process ensures stability, ideal for compact security tags.

## 1 Introduction

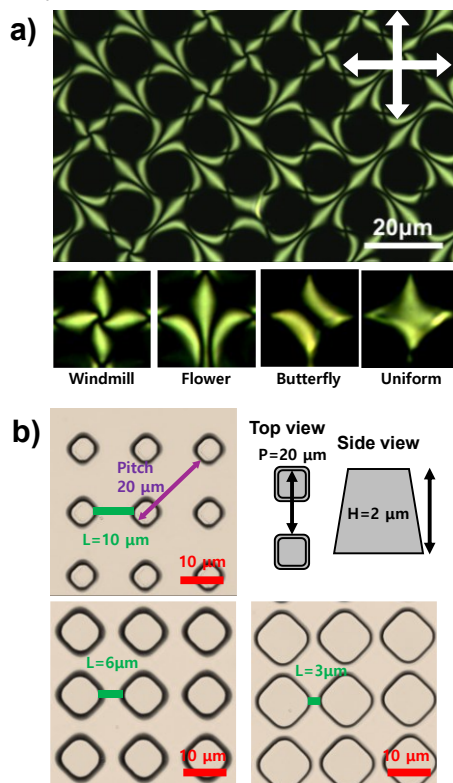
Physical unclonable functions (PUFs) represent a hardware security technology that generates unique identifiers for each device by exploiting microscopic variations occurring during the manufacturing process. Optical PUFs, which implement challenge-response pairs through light-matter interactions, have emerged as promising next-generation security technologies capable of providing high security levels without requiring complex electronic circuits or cryptographic algorithms.[1,2]

Conventional optical PUFs have been primarily implemented using random dispersion of metallic nanoparticles, surface roughness patterns, or scattering media. However, these approaches suffer from limitations including difficulty in systematic control over pattern formation and the requirement for complex and costly nanoscale fabrication processes. Additionally, ensuring stability against environmental changes and developing reproducible fabrication processes remain challenging.[3].

In this study, we propose a novel optical PUF approach utilizing the inherent self-assembly characteristics of liquid crystal materials[4]. Nematic liquid crystals, which are liquid crystalline phases possessing long-range orientational order, spontaneously form various director arrangement structures depending on boundary conditions and geometric constraints. Particularly, topological defect structures formed through phase transition processes on micropatterned substrates exhibit unique optical properties (Fig. 1a)[5].

In the proposed system, the diversity and randomness of liquid crystal director patterns can be simultaneously controlled by systematically adjusting the geometric parameters of Micropattern substrates (Fig. 1b), specifically the channel width between adjacent compartments. These structural characteristics are converted into unique optical fingerprints through polarized optical systems, thereby implementing PUF

functionality.



**Fig. 1.** a) POM images of patterns formed on the Micropattern substrate. b) Schematic illustration of Micropatterns substrate parameters.

## 2 Experimental Methods

### 2.1 Micropatterns Substrate Fabrication

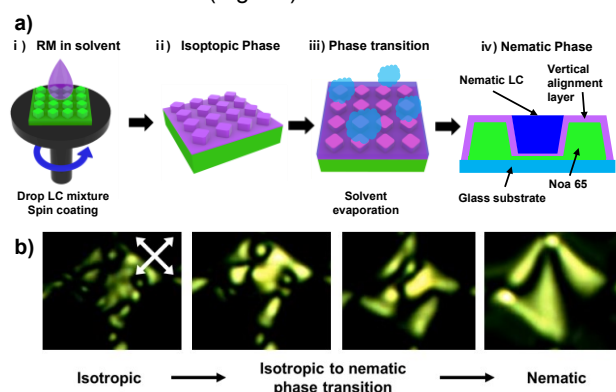
Glass substrates of 2.5 × 2.5cm were used as the base material. The substrate surfaces were first ultrasonically cleaned with acetone and isopropanol, followed by nitrogen drying. For photolithography processing, UV-curable adhesive (NOA65, Norland Optical Adhesive, viscosity 300 cps) was uniformly applied via spin coating (2000rpm, 60s).

A contact lithography system using chrome masks was employed for micropattern formation. The mask was designed in a square lattice configuration, with systematic variation of individual cell sizes and intercell channel widths. UV exposure (365nm, intensity 20mW/cm<sup>2</sup>) for 15 minutes produced cylindrical microcolumn arrays with height 2±0.1 μm and pitch 20

$\mu\text{m}$ . (Fig. 1b).

Channel width, the most critical geometric parameter for liquid crystal pattern formation, was precisely controlled through photomask design within the range of  $0\mu\text{m}$  (complete isolation) to  $10\mu\text{m}$ . After exposure, unreacted resin was removed and final UV curing (30 minutes) was performed to complete the robust microstructures.

To control interfacial properties with liquid crystals, vertical alignment layers were introduced. Polyimide (vertical alignment, Albatrace) solution was spin coated (3000rpm, 30s) followed by thermal treatment at  $130^\circ\text{C}$  for 1 hour to induce strong vertical anchoring at the substrate-liquid crystal interface. Surface roughness measurements confirmed highly uniform alignment layers with RMS values below  $2\text{nm}$  (Fig. 2a).



**Fig. 2.** a) Process flowchart for PUF liquid crystal alignment. b) POM images of the isotropic-to-nematic phase transition within the Micropattern during heating.

## 2.2 Liquid Crystal Pattern Formation and Fixation

Reactive mesogen mixture (RMS03-013C, Merck) was employed, characterized by birefringence ( $\Delta n$ ) of 0.137 and nematic-isotropic transition temperature of  $86^\circ\text{C}$ . The mixture contains photoinitiators enabling permanent fixation of liquid crystal arrangements through crosslinking reactions upon UV irradiation.

The reactive mesogen was applied to prepared substrates via spin coating (2000rpm, 120s). Coating thickness was controlled to 0.9-1.1 times the microcolumn height, ensuring complete coverage of column tops while preventing non-uniformity due to excessive thickness.

Pattern formation was achieved by heating samples on a  $60^\circ\text{C}$  hotplate for 60 seconds. During this process, solvent evaporation simultaneously induces the isotropic-to-nematic phase transition. Throughout the phase transition, liquid crystal molecules form complex director arrangements due to competition between vertical anchoring (homeotropic) at the substrate and planar anchoring at the air interface[6][7] (Fig. 2b).

## 2.3 Optical Characterization and Analysis

Optical properties of formed liquid crystal patterns were observed using polarized optical microscopy (Olympus

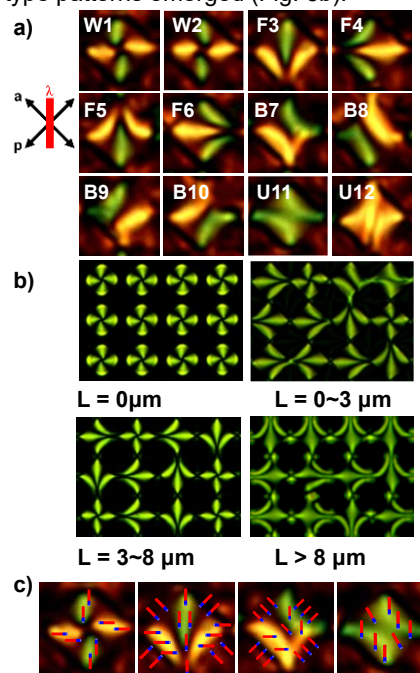
BX53,  $20\times$  objective lens). Basic observations were performed under crossed polarizer conditions, with additional use of  $\lambda/4$  retardation plates to acquire director tilt angle information.

High-resolution images were captured using a digital camera (Canon EOS-600D) under each observation condition. Optical characterization for PUF functionality was performed under various polarization conditions combining polarizer rotation angles and  $\lambda/4$  plate presence/absence. The unique optical textures of each pattern exhibit different responses to polarization condition changes, thereby providing optically distinguishable fingerprints enabling individual identification.

## 3 Results

### 3.1 Channel Width-Dependent Pattern Formation

Through systematic control of channel width, twelve distinct nematic director patterns were observed, classified into four topological families: Windmill (W1, W2), Flower (F3-F6), Butterfly (B7-B10), and Uniform (U11, U12) (Fig. 3a). At  $0\mu\text{m}$  channel width, only Windmill patterns appeared due to complete spatial isolation. The  $0\text{-}3\mu\text{m}$  range exhibited all twelve patterns with random distribution, while  $3\text{-}8\mu\text{m}$  favored Windmill and Flower configurations. Beyond  $8\mu\text{m}$ , predominantly Flower-type patterns emerged (Fig. 3b).



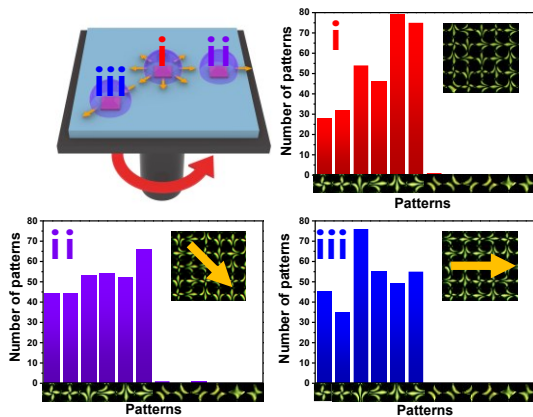
**Fig. 3.** a) POM images of all twelve director patterns, captured under crossed polarizers with a  $\lambda/4$  retardation plate. b) Representative pattern variations as a function of channel width (pitch), showing the Windmill, Flower, Butterfly, and Uniform families. c) Schematic diagrams of liquid crystal director distributions for each pattern family.

### 3.2 Topological Defect Analysis

Polarized optical microscopy with  $\lambda/4$  retardation plates revealed distinct defect structures for each pattern family. Windmill patterns exhibit central +1 defects, characteristic of vertical anchoring conditions. Flower patterns display  $\pm 1/2$  defect pairs at compartment corners, stabilized by intercell connectivity. Butterfly and Uniform patterns show line defects with different orientations. All patterns satisfy topological charge conservation ( $\sum q_i = 0$ ) (Fig. 3c).

### 3.3 Spatial Distribution Uniformity

Analysis across the 2.5cm  $\times$  2.5cm substrate revealed consistent pattern formation despite potential thickness variations from spin coating (Fig. 4). All topological families appeared uniformly across different substrate regions, demonstrating process robustness and spatial consistency suitable for reproducible PUF applications.



**Fig. 4.** Spatial pattern distribution uniformity across a glass substrate divided into three regions: i (red) center, ii (purple) edge under oblique stress, and iii (blue) edge under lateral stress.

## 4 Discussion

The primary advantage of this Micropattern liquid crystal PUF lies in fabrication simplicity using standard glass-based photolithography, eliminating the need for complex nanoscale processing while achieving effective PUF functionality. The liquid crystal self-assembly enables "controlled randomness" - systematic geometric control through channel width while maintaining intrinsic pattern randomness, making external prediction or replication extremely difficult.

The diversity of twelve topological patterns, each with unique defect charge distributions, provides clearly distinguishable optical signals through polarized microscopy. Multi-polarization measurements using  $\lambda/4$  retardation plates significantly enhance security capabilities.

Spatial uniformity across 2.5cm substrates demonstrates process robustness suitable for compact security device applications. Future work will focus on integration with on-chip polarized optical readout systems

and pattern density optimization for enhanced security performance.

## 5 Conclusion

We successfully developed a novel optical PUF methodology utilizing nematic liquid crystal phase transitions on Micropattern glass substrates. Channel width control enables formation of twelve distinct topological patterns, providing unique optical fingerprints for effective PUF functionality. The simple glass-based fabrication process ensures excellent reproducibility and environmental stability, making it suitable for practical security device applications.

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