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Decoupling degrees of freedom in optical encryption

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Abstract

A biphasic chiral photonic crystal has been shown to support four structurally orthogonal encryption keys by exploiting physical and optical orthogonality. These results open new opportunities to engineer combinatorial key spaces in photonic platforms and for applications in optical security and anti-counterfeiting.

Keywords: Chiral photonic crystals, Optical encryption, Liquid crystal photonics

Information security is a defining challenge of the digital era. Conventional electronic encryption faces an existential threat from quantum computing given that such algorithms can reduce problems that underpin classical cryptography to polynomial complexity[1]. Physical-layer optical encryption offers a qualitatively different resistance; by encoding information in the physical properties of light itself, the computational complexity of security measures can, in principle, increase much faster than that of potential attacks[2–6]. Landmark demonstrations spanning orbital angular momentum (OAM) holography[7], stimuli-responsive chiral photonic crystals[8], cascaded metasurface secret sharing[9], and reprogrammable meta-holograms[10] have each extended the nominal key space of optical encryption systems.

Nonetheless, a persistent and underappreciated subtlety limits many of these demonstrations. In single-component chiral photonic crystals, the degrees of freedom of light are not independently controllable; rather, they are correlated through a given structural parameter. In a cholesteric liquid crystal (CLC), the helical pitch simultaneously determines the reflection wavelength, the circular polarisation-handedness selectivity, and the Bragg–Berry geometric phase[11,12]. Similarly, although polymer-stabilised blue-phase liquid crystals (PS-BPLCs) exhibit a remarkable thermal robustness of their 3D photonic lattice, they operate at a single fixed Bragg wavelength and one circular polarisation handedness[13]. Cascaded liquid crystal (LC) and metasurface devices push the channel count higher but typically leave spin and wavelength entangled through the shared Bragg condition[14]. This means that in practice, multi-parameter systems offer a key space that is at best additive and lack the combinatorial growth that genuine independence would provide[15].

Ouyang et al. recently reported a biphasic chiral photonic crystal platform that fundamentally resolves the coupling problem[16]. A right-handed PS-BPLC is formed inside a photopatterned cell and treated with solvent to remove unreacted monomers. The polymer network contracts irreversibly, which opens an atmospheric gap that is subsequently refilled with a left-handed CLC (LH-CLC). This results in two co-existing photonic crystal phases within a single cell. Their opposite handedness provides structurally orthogonal spin selectivity, and the PS-RH-BPLC reflects only right-handed circular polarisation

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(RCP) at a thermally stable wavelength fixed by its locked polymer lattice, while the LH-CLC reflects only left-handed circular polarisation (LCP) at a wavelength that shifts continuously from 650 to 580 nm as the temperature falls from 80 °C to room temperature. Each phase carries its own independently photopatterned alignment distribution, and thus neither phase optically perturbs the other, the schematic of multichannel optical encryption is shown in Fig. 1.

This orthogonality has been shown to enable dual-channel operation unavailable in prior single-medium devices. In the near-field channel, circular-polarisation interference in a 4*f* imaging system revealed an image of a "flower" encoded in the LH-CLC and an image of "leaves" in the PS-RH-BPLC. The flower was visible only below the CLC clearing temperature, and its colour drifted thermochromically upon cooling. Meanwhile, the leaves remained spectrally and spatially stable at all temperatures. In the far-field holographic channel, two Gerchberg-Saxton holograms encoding the geographic coordinates of Nanjing were reconstructed only when σ, λ, and T were simultaneously correct. At elevated temperatures, CLC was isotropic, and the longitudinal hologram was simply absent regardless of polarisation or wavelength. Meanwhile, at room temperature, 500 nm LCP revealed the longitude, and 540 nm RCP revealed the latitude. Spin crosstalk was negligible not due to algorithmic filtering but rather because the two layers were physically transparent to each other's operating conditions.

Research on optical encryption has increasingly pursued multi-parameter platforms, with the implicit assumption that each additional degree of freedom expands the key space proportionally. This work exposes a structural flaw in that logic: in a single-phase chiral photonic crystal, spin, wavelength, and phase modulation all share a common origin and cannot be varied independently. Thus, nominally multi-parameter systems only offer an additive key space at best. By decoupling these axes at the fabrication level rather than through modulation schemes, the biphasic platform reframes the central design question from that of how many parameters can be addressed to that of how many such parameters are structurally orthogonal. Table 1 positions this result against some representative approaches in the field.

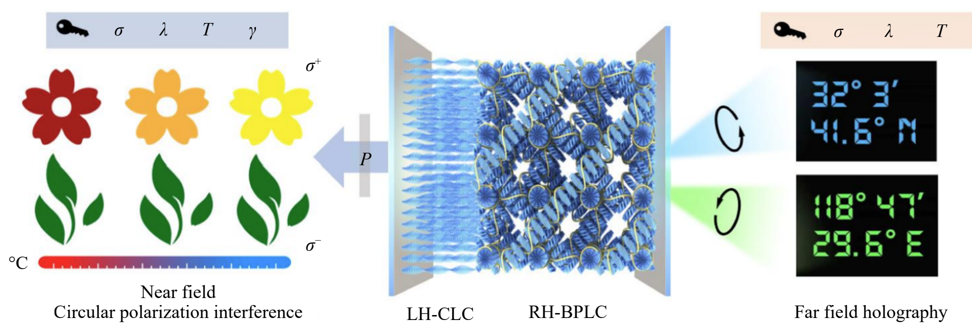

Fig. 1 Schematic of multichannel optical encryption using photopatterned biphasic chiral photonic crystals. Reprinted with permission from Ref. 16. Copyright 2026, Springer Nature.

Table 1 Representative optical encryption platforms.

Platform	Degrees of freedom (DoF)		Independence*	Key capability
	DoF	DoF utilized		
Metasurface[17]	1	σ	\	Holography, information density near the capacity limit
Metasurface[10]	1	phase	\	Electrically switchable encryption, dynamic key updating
Metasurface[7]	1	OAM	\	10-bit OAM-encoded hologram, high-security encryption
Metasurface[18]	2	λ, OAM	Yes	118 independent images, 2-nm linewidth wavelength selectivity
Metasurface[19]	2	OAM, SAM	Yes	Full AM multiplexing, nested encryption in a single layer
Metasurface[9]	1	Relative translational alignment	\	Secret sharing, scalable stack
LC[20]	2	λ, time	No	Multi-stable, erasable anti-counterfeiting
LC[8]	2	Thickness, stretching	No	Multi-wavelength IR extension, spatial pixel array encryption
LC[21]	3	σ, phase, amplitude	Partially	Tunable full-vectorial field, dynamic multichannel encryption
Biphasic LH-CLC + PS-RH-BPLC[16]	**4**	**σ, λ, T, γ**	**Yes**	**Near-field imaging, far-field holography**

* Independence indicates whether the listed parameters can be varied without mutual structural constraint within a given device.
Abbreviations: SAM - spin angular momentum

Looking forward, the principle of structural orthogonality demonstrated here points to several underexplored directions in optical encryption. In terms of materials, the biphasic architecture is not restricted to the CLC/BPLC pair. Any two photonic crystal phases with opposite handedness and non-overlapping Bragg conditions could be integrated by the same route. Thus, the operating range could be extended into the infrared region, or nonlinear and luminescent channels could be incorporated for additional encryption dimensions. In terms of encryption systems themselves, combining such platforms with on-chip photonic integration could bring multi-key optical security within reach to enable practical deployment at scale for applications in secure communications, hardware authentication, and anti-counterfeiting technologies[22,23].

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Conflict of interest

The authors declare no competing interests.

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References

1. O' Brien, J. L. Optical quantum computing. *Science* **318**, 1567-1570 (2007).
2. Zhang, J. R. et al. Multidimensional multiplexing geometric phase metaholography. *Light: Advanced Manufacturing* **6**, 474-485 (2025).
3. Zhao, M. Z. et al. Time-programmable coloration via 3D metastructures for optical encryption. *Light: Science & Applications* **15**, 118 (2026).
4. Guo, X. Y. et al. Stokes meta-hologram toward optical cryptography. *Nature Communications* **13**, 6687 (2022).
5. Liu, Z. Y. et al. Broadband spin and angle co-multiplexed waveguide-based metasurface for six-channel crosstalk-free holographic projection. *eLight* **4**, 7 (2024).
6. Li, J. X. et al. Addressable metasurfaces for dynamic holography and optical information encryption. *Science Advances* **4**, eaar6768 (2018).
7. Fang, X. Y., Ren, H. R. & Gu, M. Orbital angular momentum holography for high-security encryption. *Nature Photonics* **14**, 102-108 (2020).
8. Nam, S. et al. Programmable optical encryption using thickness-controlled stretchable chiral liquid crystal elastomers. *Light: Science & Applications* **14**, 136 (2025).
9. Georgi, P. et al. Optical secret sharing with cascaded metasurface holography. *Science Advances* **7**, eabf9718 (2021).
10. Qu, G. Y. et al. Reprogrammable meta-hologram for optical encryption. *Nature Communications* **11**, 5484 (2020).
11. Kobashi, J., Yoshida, H. & Ozaki, M. Planar optics with patterned chiral liquid crystals. *Nature Photonics* **10**, 389-392 (2016).
12. Liu, J. L. et al. Visible-light-programmed patterning in dynamically bonded cholesteric liquid crystal elastomer. *Nature Communications* **15**, 10367 (2024).
13. Zhang, X. et al. Three-dimensional electrochromic soft photonic crystals based on MXene-integrated blue phase liquid crystals for bioinspired visible and infrared camouflage. *Angewandte Chemie International Edition* **61**, e202211030 (2022).
14. Zhang, D. W. et al. Cascaded chiral birefringent media enabled planar lens with programable chromatic aberration. *PhotoniX* **5**, 17 (2024).
15. Yuan, R. et al. Spin-decoupled transflective spatial light modulations enabled by a piecewise-twisted anisotropic monolayer. *Advanced Science* **9**, 2202424 (2022).
16. Ouyang, C. et al. Multi-parameter enhanced optical encryption with biphasic chiral photonic crystals. *Light: Science & Applications* **15**, 266 (2026).
17. Wang, J. et al. Unlocking ultra-high holographic information capacity through nonorthogonal polarization multiplexing. *Nature Communications* **15**, 6284 (2024).
18. Meng, W. J. et al. Ultranarrow-linewidth wavelength-vortex metasurface holography. *Science Advances* **11**, eadt9159 (2025).
19. Yang, H. et al. Angular momentum holography via a minimalist metasurface for optical nested encryption. *Light: Science & Applications* **12**, 79 (2023).
20. Zheng, Z. G. et al. Digital photoprogramming of liquid-crystal superstructures featuring intrinsic chiral photoswitches. *Nature Photonics* **16**, 226-234 (2022).
21. Wang, Z. Y. et al. Vectorial liquid-crystal holography. *eLight* **4**, 5 (2024).
22. Zhao, R. Z. et al. Multichannel vectorial holographic display and encryption. *Light: Science & Applications* **7**, 95 (2018).
23. Wang, K. et al. All-silicon multidimensionally-encoded optical physical unclonable functions for integrated circuit anti-counterfeiting. *Nature Communications* **15**, 3203 (2024).