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Liquid–crystal-enabled dynamic optical coherence modulation for optical imaging

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Abstract

Optical coherence is a fundamental yet underexploited degree of freedom for controlling light–matter interactions, with far-reaching implications for imaging, information processing, and photonic computing. Despite decades of progress, dynamic coherence control has remained constrained by an inherent trade-off: low efficiency, bulky system footprints, and limited dynamic tunability. These limitations severely constrain the integration and miniaturization of coherence-engineered photonic systems. Here, we propose and experimentally demonstrate a dynamic Pancharatnam–Berry phase nematic liquid–crystal device, photopatterned with programmable ultraviolet polarization, which addresses several key challenges in conventional coherence-control approaches, including compactness, reversibility, and dynamic tunability. By exploiting the electro-optical reorientation of soft-matter liquid crystals, our platform enables on-demand, reversible modulation of optical coherence within a millimeter-scale device, achieving a modulation efficiency up to 70% and a response time of 20 ms. This approach realizes continuous and fully dynamic coherence tuning, spanning the entire range from nearly coherent to nearly incoherent illumination. Beyond its fundamental significance, the demonstrated capability enables enhanced optical performance in scattering environments, including speckle-free imaging and dynamically reconfigurable “smart-window” functionality. Our results establish liquid–crystal-enabled coherence engineering as a compact, efficient, and scalable solution, opening a practical pathway toward integrated and miniaturized photonic systems for next-generation imaging, encryption, and photonic computing.

Keywords: Liquid crystals, Optical coherence, Optical imaging

Introduction

Tailoring multiple degrees of freedom of light—encompassing amplitude, frequency, phase, polarization, orbital angular momentum, and beyond—has become a cornerstone of modern photonics [1, 2], driving advances in communications, imaging, metrology, and quantum information [3–8]. Among these, optical coherence stands out as a distinctive and versatile property of partially coherent beams (PCBs), characterizing the degree of correlation between the electric fields at different points in space and time [9]. By judiciously tuning coherence, one can effectively suppress unwanted interference and substantially reduce the sensitivity to external phase perturbations, thereby enabling

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speckle-free optical imaging, coherence tomography, high-fidelity information encryption, and parallel photonic computation [10–21]. Furthermore, optical coherence serves as a novel degree of freedom for information encoding, facilitating robust, high-fidelity data transmission through turbulent atmospheric channels [22, 23]. Several strategies have been developed to control the optical coherence, including rotating diffusers, spatial light modulators (SLMs), disorder-engineered metasurfaces, custom-designed scattering media, and multi-mode interferometric architectures, and electro-optical modulators based on lithium-niobate films [10, 18, 19, 24–29]. They still face trade-offs between dissipation, bulkiness, and limited reconfigurability. A compact, energy-efficient, and dynamically reconfigurable solution is in urgent demand to meet the requirements of integrated optical systems and portable instrumentation.

Liquid crystals (LCs) [30, 31] are inhomogeneous anisotropic materials that exhibit unique properties intermediate between liquids and crystals. As an easily accessible material, LCs have been widely applied not only in flat panel displays, but also as an efficient optical solution in many non-display fields [32]. Due to the birefringence and sensitive response to various external stimuli, such as heat [33, 34], electric field [35, 36], and light irradiation [37, 38], LCs have emerged as a promising platform for dynamic light modulation. In particular, LCs provide an effective platform for manipulating the Pancharatnam–Berry (PB) phase, which originates from the photonic spin–orbit interaction and is usually proportional to the orientation angle of localized LC director [39, 40]. Recent years have witnessed impressive progress in PB-phase LC devices with numerous functionalities, such as optical vortex generation [41, 42], dynamic colored holography [43, 44], and multi-functional imaging [45, 46]. Recently, Spiller and Wdowiak et al. have used LC-based dynamic scattering devices for speckle reduction in laser projection and coherent-artifact suppression in digital holographic microscopy [47, 48]. These advances further motivate the deterministic design and continuous tuning of prescribed spatial coherence states using LC platforms. It remains largely unexplored, yet highly attractive, to harness LCs to customize PCBs on demand and dynamically tune their optical coherence.

Here, we propose a PB-phase LC device to dynamically customize the optical coherence of structured light. PCBs with distinct coherence levels are flexibly generated and their degrees of coherence are quantified from measuring speckle ensembles. Leveraging voltage-dependent reorientation of the LCs, the diffraction efficiency of the LC device can be tuned together with the relative weight of modulated versus unmodulated light components, which directly determines the overall spatial coherence. This platform delivers near-unity-to-near-zero fringe visibility on demand and enables speckle-free imaging with low speckle contrast. LC-induced dynamic coherence tuning can further function as an optical smart window, enabling control over whether images can penetrate or remain obscured.

Results

Customization of optical coherence based on PB-phase LC device

Optical coherence, as the statistical degree of freedom of light, is typically represented by the degree of coherence function. In the space-frequency domain, this function of any

PCB is defined by the normalized statistically stationary function-cross-spectral density function $W(\mathbf{r}_1, \mathbf{r}_2)$, i.e.,

$$\mu(\mathbf{r}_1, \mathbf{r}_2) = \frac{W(\mathbf{r}_1, \mathbf{r}_2)}{\sqrt{W(\mathbf{r}_1, \mathbf{r}_1)}\sqrt{W(\mathbf{r}_2, \mathbf{r}_2)}}, \quad (1)$$

where $\mathbf{r}_1$ and $\mathbf{r}_2$ are two arbitrary spatial position vectors [9]. The modulus of the degree of coherence function $|\mu|$ lies within the interval $[0, 1]$. As it decreases from 1 to 0, the beam transitions from being fully coherent to completely incoherent. For simplicity, we consider only the Schell model type, i.e., $\mu(\mathbf{r}_1, \mathbf{r}_2) = \mu(\mathbf{r}_1 - \mathbf{r}_2)$. To accurately construct the degree of coherence, we employed the random phase screen method to achieve the random phase $\psi(\mathbf{r}) = \arg[T(\mathbf{r})]$ with $T = F_T \left[\sqrt{F_T^{-1}[\mu]} C_n \right]$, where “arg” represents the argument of the complex field. F_T and F_T^{-1} respectively denote the Fourier and inverse Fourier transform. C_n is a random complex matrix following a circular complex normal distribution. The speckles induced by such random phases obey the Gaussian statistics. More details could be found in Refs. [19, 49]. Therefore, the construction of the degree of coherence aims to generate a random phase function ψ . More details on the principle of coherence modulation are provided in Supplementary Note 1.

LCs provide a programmable platform for tailoring the PB phase through precise control of the LC orientation, thereby enabling the customization of the designed random phase. As illustrated in the top-left inset of Fig. 1, the director of LC molecules is characterized by the in-plane azimuthal angle φ and the out-of-plane tilt angle θ . When circularly polarized light passes through the LC device, its helicity is reversed, and it acquires a PB phase governed by φ [32] (more details in the Supplementary Note 2). The in-plane azimuthal φ conforms to the theoretical phase distribution described by $\psi(\mathbf{r}) = 2\varphi(\mathbf{r})$, which is designed to

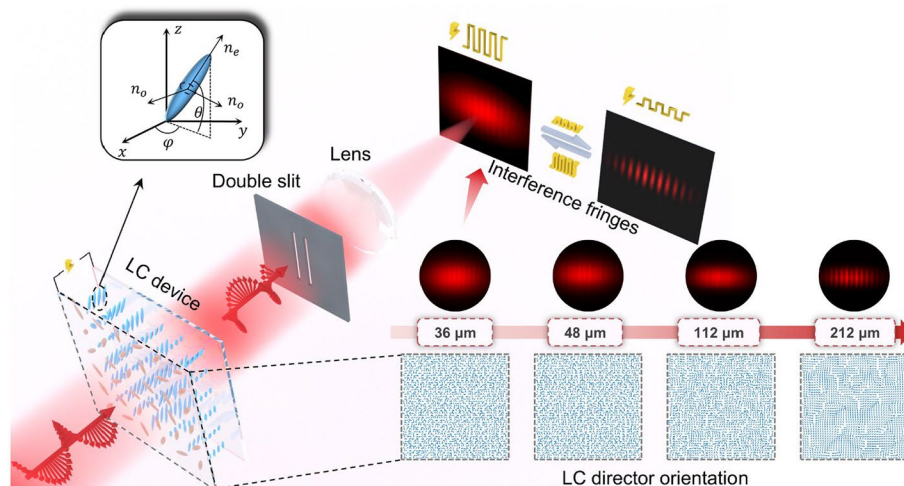


Fig. 1 LC-enabled dynamic coherence control. Schematic of the PB-phase LC platform and its double-slit characterization. When circularly polarized light is incident on the LC device with a half-wave condition, it converts into the opposite polarization state and acquires a PB phase, resulting in PCBs with reduced coherence. By applying a suitable voltage to the LC device, the coherence of the emitted beam can be dynamically tuned. The top-left inset illustrates the azimuthal angle (φ) and tilt angle (θ) of the LC molecules, and the bottom-right insets present the in-plane LC director orientation corresponding to four distinct coherence levels. The more disordered the orientation, the lower the optical coherence

reduce the coherence of light. This random phase design determines the local in-plane orientation of LC molecules, ensuring that the azimuthal angles follow the desired optical axis distribution. The bottom-right inset of Fig. 1 presents the distribution of LC molecular orientations corresponding to four distinct coherence levels. By applying external voltages, the tilt angle θ of the LC molecules can be tuned, thereby modulating the device's diffraction efficiency and dynamically adjusting the spatial coherence of the output beam. The variation in optical coherence is qualitatively evaluated through Young's double-slit interference fringes, where greater fringe visibility indicates higher coherence.

The fabrication process of the LC device is shown in Fig. 2a. Two ITO substrates spin-coated with SD1 layers were formed into a sandwich-like cell with certain spacers, and then it was exposed to ultraviolet (UV) light to load the pre-designed phase structure and filled with nematic LCs [50]. Figure 2b illustrates the principle of optical coherence modulation, including a schematic of the LC director orientation and a polarized optical micrograph of the fabricated LC device. The fabrication process of the LC device and the coherence modulation procedure in the experimental setup are detailed in the Methods section. With the LC device mounted on a two-axis translation stage and scanned horizontally and vertically, independent speckle patterns were generated as shown in Fig. 2c. The intensity profiles correspond to the central cross sections, $I(x, 0)$, of the two-dimensional intensity distributions, then PCBs were obtained by averaging over a large ensemble of these speckle patterns. In our study, a locally stationary approximation is adopted. Within the local region used for statistical analysis, the ensemble average can be approximated by averaging over independent speckle realizations. The averaged intensity can be expressed as $\bar{I}(\mathbf{r}) \approx \sum_n I_n(\mathbf{r}) / N$, where $I_n(\mathbf{r})$ denotes the speckle realizations and N is the total number of patterns. Because the speckle field generated by the LC device follows Gaussian statistics, the degree of coherence can be retrieved from fourth-order intensity correlations using the Gaussian moment theorem [9]:

$$|\mu(\mathbf{r}_1, \mathbf{r}_2)|^2 = \frac{\langle I(\mathbf{r}_1)I(\mathbf{r}_2) \rangle}{\langle I(\mathbf{r}_1) \rangle \langle I(\mathbf{r}_2) \rangle} - 1 \approx N \frac{\sum_n I_n(\mathbf{r}_1)I_n(\mathbf{r}_2)}{\sum_n I_n(\mathbf{r}_1) \sum_n I_n(\mathbf{r}_2)} - 1. \quad (2)$$

To exemplify this principle, we consider a Gaussian Schell-model beam, whose intensity profile and the degree of coherence function are both Gaussian. Its cross-spectral density is given by

$$W(\mathbf{r}_1, \mathbf{r}_2) = \exp\left(-\frac{\mathbf{r}_1^2 + \mathbf{r}_2^2}{4\sigma_0^2}\right) \exp\left[-\frac{(\mathbf{r}_1 - \mathbf{r}_2)^2}{2\delta_0^2}\right], \quad (3)$$

where σ_0 and δ_0 denote the beam width and coherence width, respectively. In this strategy, the beam profile is determined by the incident beams, and the degree of coherence function is customized by the fabricated LC device. To verify this, four different coherence widths were implemented with beams at the same beam width $\sigma_0 = 0.4$ mm. Figure 3 summarizes the experimental characterization of engineered PCBs. The top row shows the averaged intensity distributions together with representative speckle patterns, the middle row presents the corresponding maps of $|\mu(\mathbf{r}_1, \mathbf{0})|^2$, and the bottom row compares the experimental data with theoretical predictions. Figure 3c plots

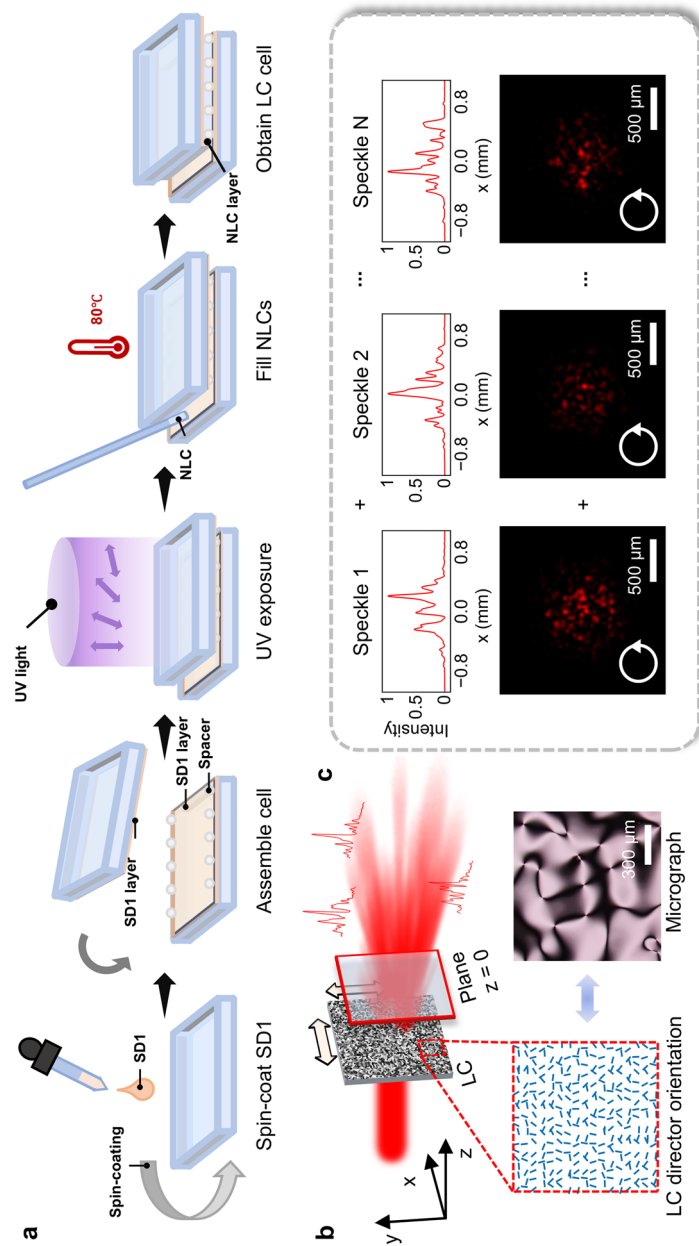


Fig. 2 Fabrication of LC device and collection of speckle patterns. **a** Fabrication process of the LC device. **b** Schematic diagram of optical coherence modulation using the LC device. The LC device is positioned at the plane $z=0$. The red dashed box highlights the local LC director orientation angle. The right panel displays an optical micrograph of the LC device under crossed polarizers. **c** Representative speckle frames and the corresponding one-dimensional cross-sectional intensity profiles were obtained via two-dimensional scanning of the LC device

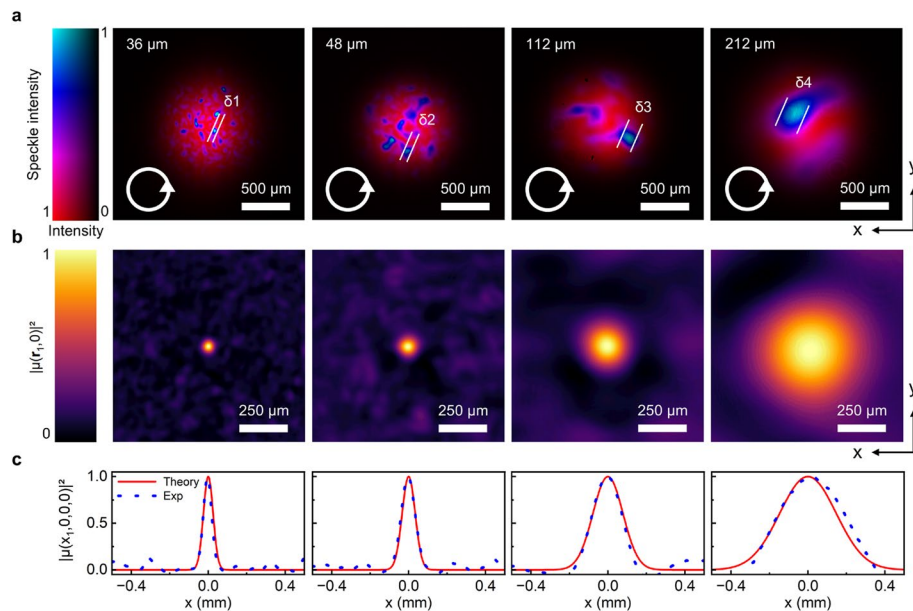


Fig. 3 LC-engineered Gaussian Schell-model beams. **a** Averaged intensity profiles together with representative speckle patterns generated by the LC device at four coherence widths under the same beam width $\sigma_0 = 0.4$ mm. **b** Maps of the square of the modulus of the degree of coherence function retrieved via fourth-order correlation analysis. **c** One-dimensional cross-sectional profiles along $y=0$ (data: Blue dashed; Gaussian fit: Red solid)

$|\mu(x_1, 0, 0, 0)|^2$ along $y_1 = 0$ where the experimental data (blue dashed curves) agree well with Gaussian fits (red solid curves). As the coherence width increases from left to right, the speckle grain size becomes larger, consistent with broader $|\mu|^2$ profiles. The retrieved coherence widths of 36, 48, 112, and 212 μm confirm that controlled LC orientation enables effective and quantitative tuning of the spatial coherence, the micrographs of the LC devices for 36 and 212 μm widths are shown in Supplementary Note 3. Possible noise-induced deviations in the retrieved coherence values, particularly for low-coherence states, were reduced by background subtraction, optimized exposure conditions, sufficient optical power, and ensemble averaging over a sufficiently large number of independent speckle realizations. This method is not limited to Gaussian Schell-model beams, but can also be extended to partially coherent fields with special correlation structures, such as cosine-Gaussian correlated Schell-model beams; further details are provided in Supplementary Note 4.

Electro-optical tuning: from near-coherent to near-incoherent

Dynamic control of optical coherence offers significant tools in studying the light-matter interactions driven by coherence, as well as in coherence-related applications. To achieve this dynamic control, we leverage the notable features of LCs: their excellent electro-optical tunability. The voltage-dependent reorientation of LC molecules (Fig. 4a and b) enables flexible modulation of the diffraction efficiency of the LC device. It should be emphasized that the applied voltage changes the tilt angle (θ) of the LC molecules and thus modifies their effective phase retardation. As a result, the

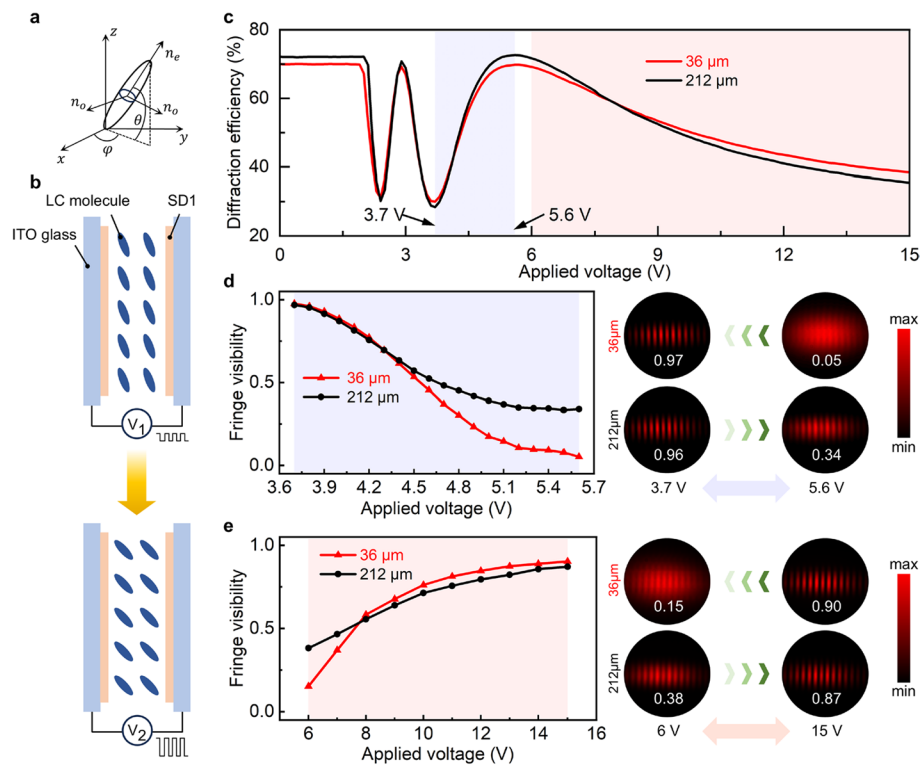


Fig. 4 Electro-optical tuning of the optical coherence. **a** LC molecular orientation, determined by tilt angles (θ) and azimuthal angles (ϕ). **b** Schematic diagram of the LC device when applying external voltage. **c** Diffraction efficiency of the LC device under varying applied voltages. **d** Variation in the visibility of double-slit interference fringes as the applied voltage increases from 3.7 V to 5.6 V (rising region of diffraction efficiency). **e** Variation in fringe visibility as the applied voltage increases from 6 V to 15 V (falling region of diffraction efficiency)

modulation efficiency changes, which alters the relative weight between the modulated component and unmodulated component, thereby dynamically tuning the spatial coherence of the output field. The double-slit mask (slit width 40 μm , separation 200 μm) was fabricated on a thin film, and a 1 kHz square-wave driving signal was applied to the LC device. As shown in Fig. 4c, the diffraction efficiency exhibits oscillatory behavior with applied voltage and follows similar trends for different static coherence widths (36 μm , red; 212 μm , black). Two regions of the curve—highlighted in light purple (rising) and light pink (falling) were analyzed to examine the optical coherence dependence in detail. Optical coherence was quantified via Young's double-slit interference, where higher fringe visibility indicated higher coherence.

In the rising region (3.7–5.6 V), the diffraction efficiency increases monotonically. At 3.7 V, the LC device is at the full-wave condition, as indicated by the left black arrows in Fig. 4c, with diffraction efficiencies dropping to 30% ($\delta_0 = 36 \mu\text{m}$) and 28% ($\delta_0 = 212 \mu\text{m}$) (Fig. 4d), respectively. Increasing the voltage to 5.6 V drives the system towards the half-wave condition, yielding maximum efficiencies of 70% ($\delta_0 = 36 \mu\text{m}$) and 73% ($\delta_0 = 212 \mu\text{m}$) in this experiment. The efficiencies reported in our work are absolute efficiencies, defined as the power ratio of the modulated component to the total incident light. In contrast, the ~90% efficiency reported for PB-phase LC devices in Ref. [32] refers to a relative efficiency, defined as the power ratio of the modulated

component to the total transmitted light. The difference between these two efficiency values mainly arises from transmission losses of the ITO glass and the polarization-analyzer system, as discussed in Supplementary Note 5. Over this voltage process, the fringe visibility decreases from 0.97 to 0.05 for the 36 μm Gaussian Schell-model beam, and from 0.96 to 0.34 for the 212 μm beam (Fig. 4d). In the falling region (6–15 V), the diffraction efficiency decreases, and the fringe visibility correspondingly increases—from 0.15 to 0.90 and from 0.38 to 0.87 for $\delta_0 = 36 \mu\text{m}$ and $\delta_0 = 212 \mu\text{m}$ (Fig. 4e), respectively. This behavior arises because low diffraction efficiency leaves most of the transmitted light unmodulated, preserving high coherence, whereas increasing diffraction efficiency enhances the modulated fraction and reduces the coherent component. The minimum achievable coherence is determined by the design of LC devices, while the maximum remains nearly constant across different devices.

These results confirm that the proposed LC devices enable continuous, reversible, and customizable modulation of optical coherence. Moreover, the analysis of the two regions reveals that selecting a region with a steeper slope in the diffraction-efficiency curve, as in the light-purple region, requires only a 0.9 V increase in the applied voltage to induce a rapid change in optical coherence. In contrast, operating in the light-pink region with a gentler slope slows the modulation but allows for more precise tailoring of the optical coherence. The overall response time is primarily limited by the electro-optical response of the LC material, and in our implementation, we achieve ~20 ms for the response time. Faster performance is feasible with alternative LC materials and device designs [18].

LC-enabled distinguished optical imaging

In scattering environments or rough surface imaging, high spatial coherence induces strong speckle noise that degrades image quality severely. Random lasers have previously been employed in reducing source coherence to suppress artifacts [10, 51]. Since LCs can enable dynamic and flexible control of optical coherence, we further investigated their application to speckle-free optical imaging, as outlined in Fig. 5a. The LC device was demonstrated to suppress speckle formation and improve image quality. In this setup, the ground glass was positioned on the illumination side of the resolution target. Experimental details are provided in the Methods section. In Fig. 5b, we investigated only the speckle patterns under different coherence widths without a mask. Under fully coherent illumination, distinct speckle grains are clearly visible. As the disorder of the customized LC director orientation increases, resulting in lower coherence, the recorded speckles gradually diminish and eventually become imperceptible.

To quantify the intensity fluctuations in speckle patterns, we used the conventional speckle contrast [52], defined as $C = \sigma_I / \langle I \rangle$, where σ_I and $\langle I \rangle$ denote the standard deviation and mean of pixel intensities, respectively. A smaller C corresponds to a more uniform image. The speckle contrast C decreases from 0.72 to 0.04 as the optical coherence decreases from a fully coherent case to low coherent $\delta_0 = 36 \mu\text{m}$. The speckle contrast $C = 0.04$ is below the threshold of human visual perception. Furthermore, we also calculated the probability density function of the pixel intensity values in the speckle pattern, which was normalized by the average intensity $\langle I \rangle$, as shown in Fig. 5d. A narrower function reflects a higher concentration of pixel intensities and thus a

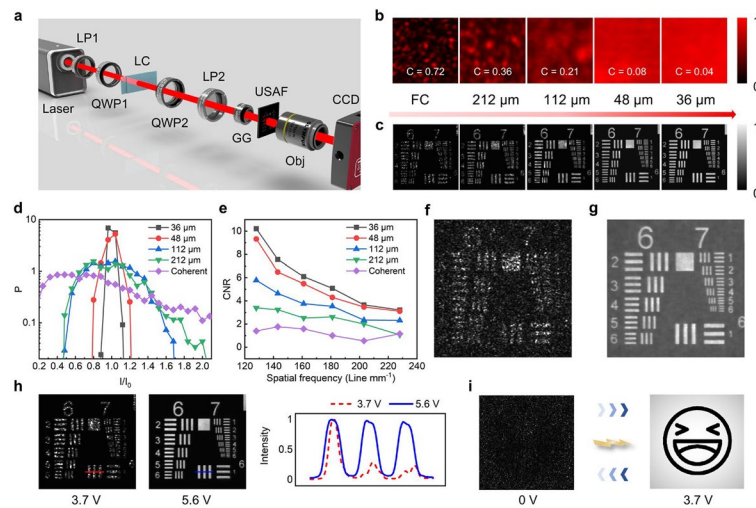


Fig. 5 LC-enabled distinguished optical imaging. **a** Experimental setup: He–Ne laser (Laser), linear polarizers (LP1, LP2), quarter-wave plates (QWP1, QWP2), liquid crystal (LC), scattering medium—ground glass (GG), resolution target (USAF), 10 × objective lens (Obj), and camera (CCD). **b** Speckle images captured with five different coherence widths. **c** Imaging results of USAF resolution target groups 6 & 7, elements 1–6. **d** Probability density function of the pixel intensity values in the speckle pattern, normalized by the average intensity $\langle I \rangle$. **e** CNR for each spatial frequency with different coherence widths based on the resolution target imaging results. The images of the USAF obtained through ground glass as the illuminations are **(f)** fully coherent and **(g)** partially coherent. **h** Combined with coherence dynamic control technology, images hidden behind LCs can be purposefully selected for display, thereby **(i)** realizing the effect of a smart window

more uniform image, consistent with the conclusion derived through the speckle contrast. To explore the impact of the LC coherence on the optical imaging quality, we adopted a USAF resolution target as the imaging object. The results are exhibited in Fig. 5c. With decreasing LC coherence, the image gradually transforms from a grainy, low-resolution pattern into a uniform intensity distribution (from left to right). To quantify image quality, we adopted the contrast-to-noise ratio (CNR), defined as $CNR = (\langle I \rangle_f - \langle I \rangle_b) / ((\sigma_f + \sigma_b) / 2)$, where the subscripts f and b refer to the signal and background, respectively. A higher CNR value corresponds to a greater signal-to-background distinction and improved image quality. In the element of the USAF resolution target, the spacing between the adjacent lines is quantified in terms of spatial frequency (line pairs per millimeter), which directly indicates the achievable spatial resolution. As illustrated in Fig. 5e, overall, the CNR decreases with increasing spatial frequency. For a fixed spatial resolution, however, it increases as the optical coherence decreases. At a spatial frequency of 128 lp/mm, the CNR for a coherence width $\delta_0 = 36 \mu m$ is an order of magnitude higher than that under fully coherent illumination.

The advantages of low-coherence illumination become especially pronounced in scattering environments. To verify this, we performed imaging of the USAF through ground glass. Under fully coherent illumination (Fig. 5f), strong random scattering redistributed photons into the background, reducing contrast and obscuring fine features. The contrast-to-noise ratio (CNR) of element 1 in group 6 was measured to be 1.63 under fully coherent illumination, whereas it increased to 5.96 under low-coherence illumination. In contrast, low-coherence illumination preserved the signal–background distinction, enabling clear feature separation even in the presence of scattering (Fig. 5g).

To demonstrate dynamic control, we evaluated the imaging quality of element 1 in group 6 of the USAF resolution chart under different applied voltages within the rising region of Fig. 4c. As the voltage increased from 3.7 to 5.6 V, the LC device transitioned from full-wave to half-wave condition, improving the efficiency of the LC device and reducing coherence. Correspondingly, the lateral intensity profiles (Fig. 5h) show that the target features became easier to resolve. The electrically reconfigurable coherence further suggests a possible optical smart-window functionality, in which the transmission of spatial information can be adjusted by tailoring the applied voltage (Fig. 5i). In this coherence-based demonstration, the switching contrast is not a single universal value, but depends on the spatial-frequency content of the transmitted image. The CNR results in Fig. 5e therefore provide a quantitative guideline for evaluating the coherence-dependent image visibility at different spatial frequencies. Unlike conventional smart-window technologies that usually rely on transparency, absorption, polarization, or scattering modulation, the present mechanism controls the visibility of spatial information by tuning the spatial coherence of the illumination rather than primarily attenuating the transmitted intensity. We note that practical deployment would require further optimization and systematic evaluation of several aspects, including viewing-angle dependence, long-term cycling stability, temperature dependence, humidity tolerance, and large-area device fabrication. Nevertheless, this proof-of-concept result indicates that LC-enabled dynamic coherence modulation can provide a complementary route for information-visibility control and adaptive optical imaging. The response time is mainly governed by the viscosity, elastic constants, dielectric anisotropy, and cell thickness of the nematic LC material, and is approximately 20 ms in our implementation. For applications requiring faster modulation, the response time can be further improved by employing much faster LC materials, such as ferroelectric LCs or dual-frequency LCs.

Discussion

PB-phase LCs have been demonstrated as an efficient and compact platform for adaptive coherence engineering. Static customization is achieved by pre-programming the LC orientation that encodes the target optical coherence. The inherent electro-optical tunability of LCs contributes to continuously variant fringe visibility from near-unity to near-zero, effectively covering the entire spectrum of optical coherence. Speckle-free imaging with low speckle contrast and smart-window applications are realized on demand. Compared with conventional coherence control methods based on rotating scatterers, our approach avoids optical loss caused by nondirectional scattering. Moreover, the predesigned phase distribution provides a more integrated strategy for dynamic spatial coherence modulation, offering high efficiency ($\sim 70\%$), millimeter footprint, and dynamic reconfigurability (~ 20 ms). While the present work focuses on spatial coherence through transverse random phase modulation, the same general concept may be extended to temporal coherence engineering by applying tailored random modulation in the spectral or temporal domain. This work verifies the unexploited capability of LCs in

optical coherence control, and promotes broad implications for secure optical communications, high-quality imaging, and parallel photonic computation.

Methods

Sample fabrication

Figure 2a illustrates the fabrication process of the proposed LC device. A polarization-sensitive photoalignment agent, SD1 [50], was dissolved in dimethylformamide (DMF) at a concentration of 0.35 wt%, spin-coated onto two pieces of indium-tin-oxide (ITO) glass, and then cured at 100 °C for 10 min. These two substrates with the photoalignment layer were assembled into a sandwich-like configuration, supported by spacers to form a cell gap of 6.9 μm and sealed by an epoxy adhesive. After a multi-step partly overlapping photopatterning process with the help of linearly polarized UV light, the SD1 molecules on two substrates tended to reorient and be perpendicular to the illuminated UV polarization. As a result, the designed space-variant pattern was encoded into the empty LC cell. It was further filled with the nematic LC E7 at 80 °C and then gradually cooled to room temperature. The filled LC molecules were guided by the adjacent SD1 layer via intermolecular interaction, establishing the intended LC orientation and corresponding designed LC device.

Experimental procedure

In the experiment, fully coherent light was converted into left-handed or right-handed circularly polarized light by a combination of a polarizer and a quarter-wave plate. The light beam was phase modulated by an LC device, and the handedness was changed. The outgoing light passed through another combination of quarter-wave plate and polarizer to remove the unmodulated circularly polarized component, thereby generating a Gaussian-Schell model beam. For the voltage-dependent coherence-tuning measurements, the polarization-filtering combination placed after the LC device was removed. The LC device was mounted on a motorized 2D translation stage, and its scanning position had been pre-calibrated. Subsequently, a series of independent instantaneous speckle patterns obtained by two-dimensional spatial scanning of the LC device were recorded by a CCD camera at a fixed distance. For each coherence state discussed in the main text, we adopted 1600 independent speckle realizations obtained by two-dimensional spatial sampling of the LC device over 40×40 scanning positions for statistical analysis, thereby ensuring the stability of the statistical results.

Based on the above light sources, a speckle-free imaging experiment was further conducted. Gaussian-Schell model beams with different coherence widths were employed as illumination. To simulate scattering conditions, a ground glass diffuser was introduced either before the USAF resolution target or between the target and the objective lens. In both configurations, the transmitted light was subsequently collected by a $10 \times$ microscope objective to form the images.

All measurements were performed at a room temperature of approximately 24 °C and a relative humidity of approximately 30%.

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s43074-026-00275-x>.

Supplementary Material 1.

Acknowledgements

Not applicable.

Authors' contributions

C.H.L. and P.C. conceived the idea and developed the theory. Y.L.B. and S.N.C. verified the theoretical framework and performed the simulations and experiments. Q.C., X.L., and W.C. completed the data analysis and visualizations. C.H.L., P.C., Y.L.B., and S.N.C. contributed to drafting and finalizing the manuscript. Y.Q.L. and Y.J.C. co-supervised the project. All authors participated in the discussion and review of the manuscript.

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Data availability

The data that support the findings of this study are available from the authors upon reasonable request.

Declarations

Competing interests

The authors declare no competing interests.

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