

RESEARCH ARTICLE

Time-Varying Active Flat Optics Driven by a Constant Light Stimulus

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ABSTRACT

Flat optics compresses bulky optical functions into structured ultrathin layers, and making such components active—able to change their optical response after fabrication—underpins dynamic holography, beam steering, and optical information processing. However, active flat-optical elements generally require a time-varying external control signal to produce a time-varying optical output, so the temporal degree of freedom must be supplied and sustained externally. Here, a photoresponsive chiral liquid crystal is shown to supply this degree of freedom intrinsically, with a single constant light stimulus driving self-paced, time-varying optical operation. Pancharatnam-Berry patterning of the in-plane director fixes the spatial wavefront, while hybrid planar-homeotropic anchoring enables continuous through-thickness helix reconfiguration. As a result, the conversion efficiency of the pre-encoded geometric-phase wavefront oscillates over multiple cycles while the spatial diffraction pattern is preserved, and a layered Jones-matrix model links the evolving helical pitch to the measured response. Correlated fingerprint-texture and far-field dynamics track this evolution, and green light optically reverses the response. Such self-paced modulation is demonstrated across five geometric-phase elements, spanning beam deflection, vortex generation, axicon, off-axis imaging, and holographic reconstruction, establishing a transmissive, electrode-free route to time-varying active flat optics.

1 | Introduction

The ability to sculpt light across both space and time lies at the heart of modern photonics [1], underpinning dynamic beam steering [2], high-capacity optical communication [3], information encryption [4], and programmable optical computing [5, 6]. Flat optics has largely solved the spatial half of this problem. By imprinting a subwavelength phase profile, metasurfaces and other planar architectures route the phase, amplitude, and polarization of light through ultrathin layers, yielding com-

pact metalenses [7], vortex generators [8], and high-efficiency holograms [9]. Endowing such components with a temporal degree of freedom—making their optical response evolve after fabrication—is the natural next step toward active flat optics for adaptive imaging, displays, and optical information processing [10–13].

To make flat optics active, dynamic tunability has been pursued through phase-change materials [14], microelectromechanical-system (MEMS) actuation [15], electro-optic [16] and

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carrier-injection effects [17], thermo-optic modulation [18], and mechanical deformation [19]. These mechanisms add valuable degrees of freedom, but two limitations recur. First, the accessible states are often discrete or binary, or the response is resonance-limited and narrowband. Second, and more fundamental for time-domain operation, the optical output tracks the instantaneous drive: producing a time-varying wavefront requires a correspondingly time-varying external control signal, so the temporal degree of freedom is supplied and clocked from outside the device rather than by the material itself. Generating a time-dependent optical response under constant stimulation carries distinct merits [20, 21]. It removes the need for continuous temporal addressing, waveform generation, and synchronization hardware, together with the electrodes, wiring, and refresh power that these entail, offering a far more compact route to time-varying optical operation. Equally important is why a temporally structured output is important at the point of use. Human vision is preferentially sensitive to change. Luminance transients and flicker capture attention even when they fall outside the current focus of gaze, whereas static symbols and text must first be located and then read [22, 23]. In an emerging photonic information age increasingly centered on human-machine interaction, obtaining such perceptually salient, temporally structured output from simply a constant and entirely unstructured drive is thus of practical value.

Chiral liquid crystals (CLCs) offer a natural route. Combining in-plane director patterning, spontaneous 3D helical self-assembly, and continuous stimulus responsiveness, they provide the material foundation for space-time wavefront control [24–29]. Locally imprinting the in-plane orientation yields geometric-phase elements governed by the Pancharatnam-Berry (PB) phase—beam deflectors [30], geometric-phase lenses [31], *q*-plates [32, 33], and polarization holograms [34–36]—while photoresponsive chiral dopants or light-driven molecular motors continuously modify the helical pitch to give tunable diffraction or switchable focal planes [24, 37–39]. In all of these photoresponsive realizations, however, the optical state follows the applied dose: a given diffraction efficiency or focal length corresponds to a given amount of accumulated stimulus, and reaching a new state means changing the stimulus, so the temporal behavior is effectively quasi-static and externally clocked. Whether a single, unchanging stimulus can drive a spatially pre-encoded wavefront through a continuous, self-paced, multi-cycle temporal trajectory—turning the material into an intrinsic source of the temporal degree of freedom—has remained unexplored.

Here we access this dynamic regime. Using a hybrid-anchored photoresponsive CLC in a high-twist, small-pitch configuration, we show that a single constant light stimulus drives the through-thickness helix continuously through many turns, so that the conversion efficiency of a spatially pre-encoded PB wavefront does not merely tune monotonically but oscillates through a continuous, multi-cycle temporal trajectory while the in-plane phase pattern—and hence the diffraction geometry—is preserved. Because the modulation is paced by the material's own light-driven kinetics under an unchanging input, it constitutes a self-paced, time-varying primitive for flat optics, of potential use for temporal encoding, self-clocked optical operation, and dynamic holography. We resolve this behavior by simultaneously tracking the chiral fingerprint texture and the far-field diffraction

and correlating their cycle counts, and we reproduce the measured temporal response with a layered Jones-matrix model. The response is optically resettable by green light, and the same self-paced modulation is realized across five photoaligned PB elements—a polarization grating (PG), a fork grating (FG), an axicon, an off-axis lens, and a Gerchberg-Saxton hologram—spanning beam deflection, orbital-angular-momentum generation, off-axis imaging, axicon and holographic reconstruction, all built from such a photoswitchable chiral material system. Together these results establish constant-stimulus, self-paced temporal modulation as a route from static or stimulus-switched flat optics toward time-varying active flat optics.

2 | Results and Discussion

2.1 | Concept of the Hybrid-Anchored Photoresponsive CLC Platform

We first define the design principle of the hybrid-anchored photoresponsive CLC platform, in which the in-plane photoaligned director pattern determines the spatial wavefront and the out-of-plane photoresponsive chiral helix supplies the temporal degree of freedom (Figure 1a). In this framework, the in-plane optical-axis distribution is encoded in the *x-y* plane by photoalignment, allowing diverse geometric-phase elements, including an axicon, an off-axis lens, a PG, and a hologram. Along the *z* direction, the LC adopts a hybrid-anchoring configuration, where the bottom SD1 (Figure S1) alignment layer defines the spatially varying planar orientation and the top substrate imposes vertical alignment. This antagonistic boundary condition creates a 3D chiral superstructure whose through-thickness helix evolves continuously under a constant light stimulus, allowing the conversion efficiency to vary with time while the photoencoded spatial wavefront remains fixed.

Here, the material comprises the right-handed chiral dopant ChAD-3c-R (Figure 1b) dispersed in the nematic LC E7. The dynamic nature of the platform originates from the photoresponsive chiral dopant ChAD-3c-R (Figure 1b). Under constant ultraviolet (UV) illumination, the dopant undergoes *trans*-to-*cis* photoisomerization, which continuously modifies the helical twisting power (HTP) and thus changes the cholesteric pitch *p*. *p* depends on both the HTP and the concentration of the chiral dopant, following $p = \frac{1}{\text{HTP} \cdot c}$. Green-light illumination reverses this process, restoring the initial molecular state and the corresponding helical configuration. A steady optical input can therefore drive continuous helix reconfiguration and a self-paced, time-varying optical response. Unlike conventional static geometric-phase elements, the present system preserves the photoencoded spatial phase profile while its polarization-conversion efficiency evolves continuously with time.

Figure 1c depicts the hybrid-anchored photoresponsive CLC superstructures that introduce the temporal degree of freedom into a spatially pre-encoded geometric-phase element. In a conventional CLC cell with planar anchoring on both substrates (Figure S2), the helix is constrained at both ends and therefore typically supports only discrete pitch modulation (i.e., the thickness $D = m \frac{p}{2}$, *m* is an integer). To overcome this limitation, we

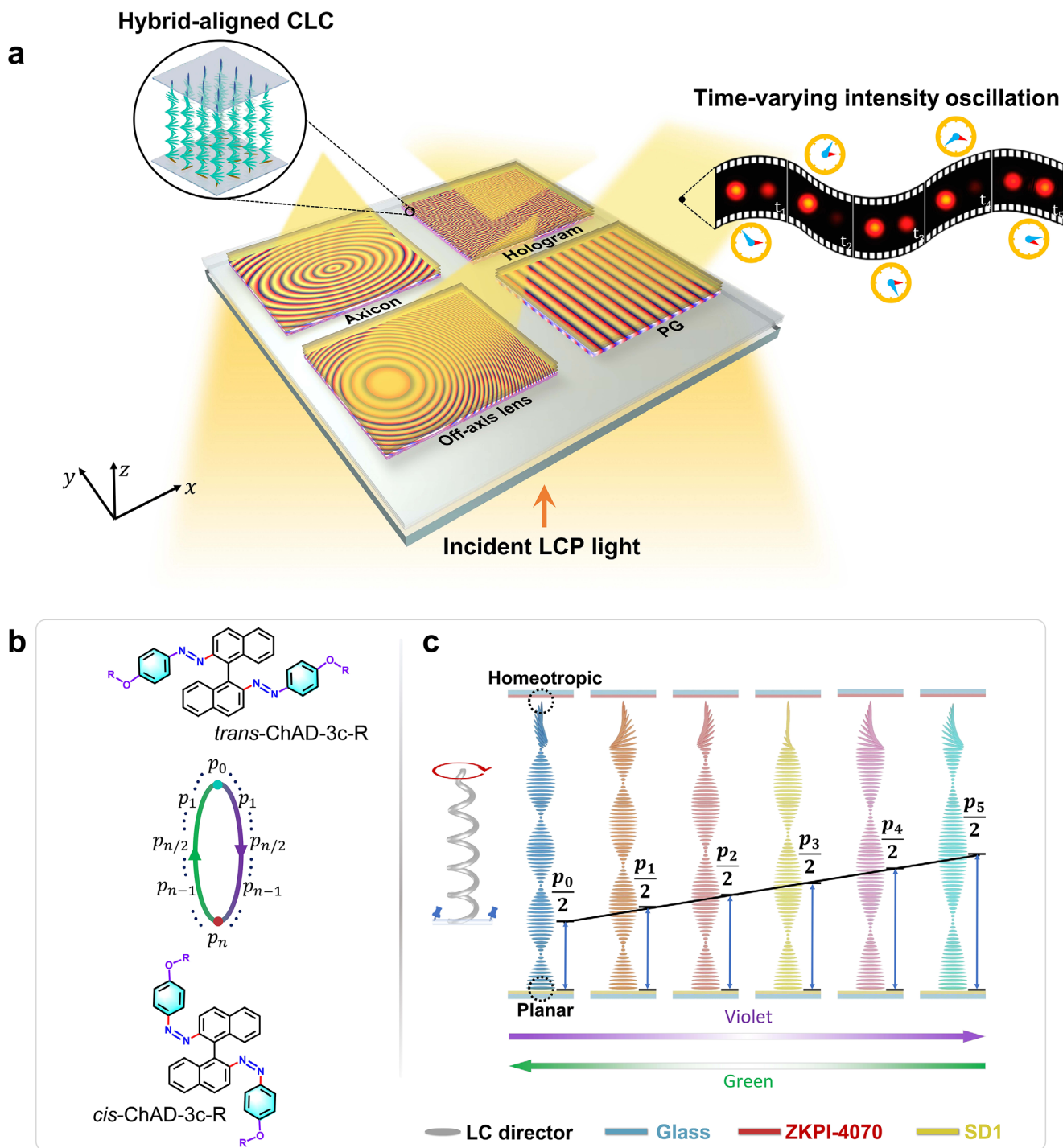


FIGURE 1 | Concept and mechanism of the hybrid-anchored photoresponsive CLC system. (a) Illustration of the hybrid-anchored photoresponsive CLC platform. Four representative elements with distinct in-plane orientation profiles in the x - y plane are presented, including an axicon, an off-axis lens, a PG, and a hologram. The 3D structure of the holographic CLC sample is shown, where yellow and blue rods represent the orientation distributions defined by the SD1 layer and the vertically aligned top layer, respectively. Under constant UV irradiation, the CLC helix evolves continuously, producing a self-paced oscillation of the transmitted diffraction intensity. The diffraction geometry encoded by the PG remains unchanged throughout this evolution. (b) Photoisomerization of the photoresponsive chiral dopant ChAD-3c-R. The chiral dopant undergoes reversible *trans*-to-*cis* isomerization under UV and green light, enabling continuous modulation of p and thereby providing the material basis for time-varying light-field modulation. (c) Schematic of the helices under the antagonistic anchoring condition, enabling continuous modulation of the output light due to the successive winding and unwinding processes. A thin ZKPI-4070 layer is coated on the upper substrate of the LC cell to perform homeotropic alignment. The other substrate is coated with a photoalignment agent SD1, which gives a planar anchoring condition. p_0 , p_1 , p_2 , p_3 , p_4 , and p_5 indicate different helical pitches during the continuous structure modulation.

employ a symmetry-breaking boundary condition by replacing the upper planar alignment with homeotropic anchoring, thereby removing deterministic in-plane azimuthal fixing. The resulting self-assembled structure consists of standing helices in the bulk and a thin interfacial fluctuation layer near the top substrate. This architecture fixes the in-plane azimuthal distribution α at the bottom surface for spatial phase encoding, while allowing the opposite end of the helix to reconfigure continuously under a constant light stimulus. Consequently, the total twist angle β evolves continuously, whereas the encoded in-plane phase profile remains unchanged. This separation between a fixed spatial wavefront and a self-paced, time-varying conversion amplitude underlies the optical responses demonstrated later.

2.2 | Temporal Characterization of the Polarization Grating

To directly verify that light-driven helical evolution produces temporal modulation of a pre-encoded optical function, we use the PG as a representative structure and simultaneously monitor its optical texture and far-field diffraction response under continuous UV irradiation (Figure 2a). In this experiment, a 633 nm left-circularly polarized (LCP) beam is used as the incident probe light, while the temporal change of the far-field diffraction pattern is recorded simultaneously with the optical texture of the PG sample (see Experimental Sections for the fabrication process of the PG sample), allowing the structural evolution of the LC to be directly linked to its optical response. The PG features a periodic and gradient phase change between 0 and 2π , whose alignment orientation is expressed as follows:

$$\alpha_{\text{PG}} = \frac{-\pi x}{\Lambda} + \alpha_0, \quad (1)$$

where Λ is the grating period and α_0 is the initial phase offset. In our device, $\Lambda = 100 \mu\text{m}$, $\alpha_0 = 0$, and the thickness of the CLC layer is $D = 9 \mu\text{m}$. This well-defined alignment distribution of LC molecules on the bottom substrate imparts a geometric phase to the transmitted light, causing the output light to diffract into specific orders. Meanwhile, light-driven evolution of the LC structure further makes this optical response vary with time.

The polarized optical micrographs show a continuous evolution of the PG microstructure during UV exposure (Figure 2b). The fingerprint texture exhibits a continuous global translation with time, indicating a collective rotation of the LC directors caused by the photoinduced unwinding of the cholesteric helix. As shown in Figure 2b, the texture shifts by one full period within 0–43 s. The local angular variation marked by the green arrows further confirms the ordered structural evolution.

This structural evolution is directly reflected in the diffraction behavior of the PG (Figure 2c). The normalized intensity of the +1st-order diffracted beam exhibits a pronounced oscillatory dependence on UV exposure time under a constant power density of $38.96 \mu\text{W cm}^{-2}$. Eight successive modulation cycles, with increasing temporal intervals, are identified. The gradual increase in the modulation period is attributed to the slowing helix unwinding process. Because the optical field completes one modulation cycle when the helical pitch changes by approxi-

mately $\frac{p}{2}$, the increasing pitch at later exposure stages requires a longer time to produce the same structural change, resulting in a prolonged temporal period. The far-field diffraction patterns and corresponding textures recorded at the six representative time points (i–vi) further show the clear correlation between the instantaneous LC microstructure and the diffracted optical field. The detailed temporal evolution of the PG texture and optical field is provided in Figure S3. These results confirm that the continuous unwinding of the CLC structure under UV irradiation modulates the diffraction efficiency in real time. Throughout this measurement the stimulus is held constant: with the UV power density fixed, the eight successive cycles—and their progressively lengthening periods—are paced entirely by the material's own light-driven helix kinetics. The chiral superstructure thus supplies the temporal degree of freedom intrinsically, producing a self-paced, time-varying optical response rather than one clocked by an external time-varying drive.

To quantitatively compare the evolution of the LC structures and the corresponding optical responses, we extract the cycle number from both the diffraction oscillation and the texture translation. Figure 2d shows nearly identical cycle-number evolution for the diffraction signal and the fingerprint texture, demonstrating that the periodic modulation of the diffraction efficiency is directly linked to the translation of the LC texture. This result reveals the close coupling between the light-driven chiral structural evolution and the optical response.

2.3 | Hybrid-Anchoring Model and Quantitative Fitting of the Temporal Response

To further elucidate the mechanism underlying the observed time-varying optical response, we establish a layered Jones-matrix model for the hybrid-aligned CLC structure (Figure 3a, b). Because the photoswitchable CLC system operates beyond the Bragg regime (i.e., $\lambda \ll n_o p$), back reflection can be neglected and the LC layer is treated as a transmissive medium. In the model, the LC layer with a total thickness D is divided into N sublayers of equal thickness $d_n = \frac{D}{N}$, and the optical response of the entire structure is obtained by multiplying the transmission matrix of each sublayer. As shown in Figure 3b, the LC director is described by the azimuthal angle $\omega(z) = \alpha + \beta(z)$ and polar angle $\theta(z)$, and can be written as:

$$\mathbf{n}(z) = \cos \theta(z) \cos \omega(z) \hat{\mathbf{x}} + \cos \theta(z) \sin \omega(z) \hat{\mathbf{y}} + \sin \theta(z) \hat{\mathbf{z}}. \quad (2)$$

Under the hybrid-anchoring condition, the LC layer consists of a bottom planar region of thickness $D - L$ and an upper tilted region of thickness L . The polar angle distribution is described as

$$\theta(z) = \begin{cases} 0, & 0 < z \leq D - L \\ \frac{\pi}{2} \frac{z - (D - L)}{L}, & D - L \leq z \leq D \end{cases}. \quad (3)$$

The directors gradually rotate out of plane, while the azimuthal angle continuously accumulates a total twist angle $\beta = \frac{2\pi D}{p}$, where p is the helical pitch. The Jones matrix of the n th sublayer is written as:

$$\mathbf{J}_n = \mathbf{R}(-\omega_n) \mathbf{G}_n \mathbf{R}(\omega_n), \quad (4)$$

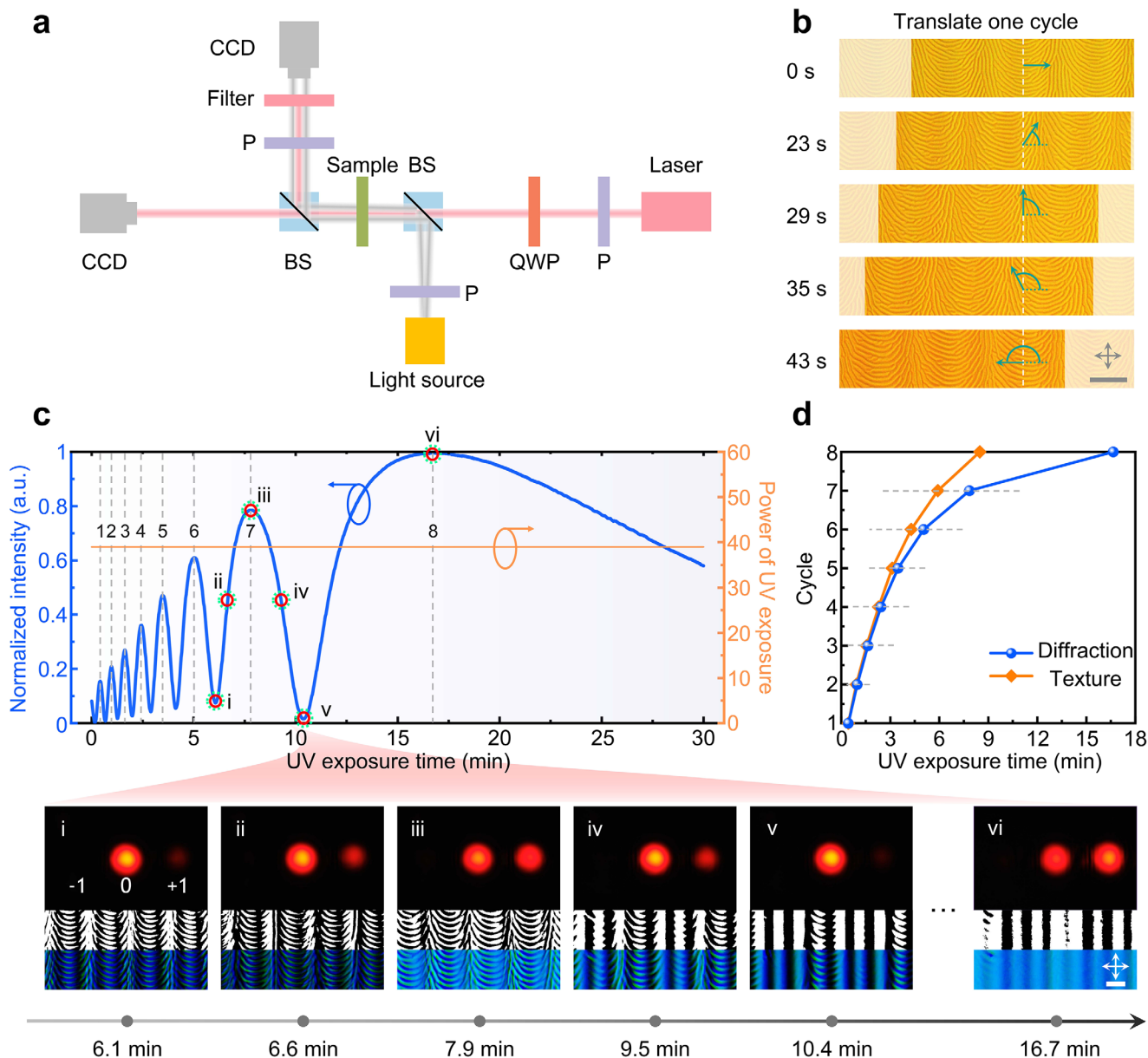


FIGURE 2 | Temporal characterization of PG. (a) Experimental setup for monitoring the temporal evolution of the diffraction signal and optical texture of the PG sample. P, linear polarizer; QWP, quarter-wave plate; BS, beam splitter; CCD, charge-coupled device. (b) Microstructure images recorded at different time points. Under continuous UV irradiation, the unwinding of the cholesteric helix induces a collective rotation of the LC directors, giving rise to a global translation of the fingerprint texture. The green arrows indicate the local angular variation of the director at the position marked by the white dashed line. Gray arrows denote the polarizer and analyzer transmission axes, respectively. (c) Normalized intensity of the +1st-order diffracted spot as a function of UV exposure time, revealing eight self-paced oscillation cycles under a fixed UV power density. The orange line indicates the UV exposure power density of $38.96 \mu\text{W cm}^{-2}$. The images below correspond to the six marked time points (i–vi), showing the associated far-field diffraction patterns and textures. (d) Comparison of the cycle numbers determined from the diffraction (blue) and the texture (orange) translation as a function of UV exposure time. All scale bars are $50 \mu\text{m}$.

where $\mathbf{R}(\omega_n)$ and $\mathbf{G}_n$ denote the rotation matrix and the phase retardation matrix of the n th sublayer, respectively. Here, $\mathbf{G}_n$ is directly related to the polar angle $\theta(z)$ through the retardation

$$\Gamma_n = \frac{2\pi[n_{\text{eff}}(\theta_z) - n_o]d_n}{\lambda}, \quad (5)$$

where $n_{\text{eff}}(\theta_z)$ is the effective refractive index of the n th sublayer. The transmission matrix of the entire LC structure is then written

as:

$$\mathbf{T} = \prod_{n=1}^N \mathbf{J}_n = \prod_{n=1}^N \mathbf{R}(-\omega_n) \mathbf{G}_n \mathbf{R}(\omega_n). \quad (6)$$

To clarify the physical origin of the time-varying modulation, Equation (6) can be rearranged as:

$$\mathbf{T} = \mathbf{R}[-(\alpha + \beta)] \prod_{n=1}^N (\mathbf{G}_n \mathbf{R}(\Delta\beta_n)) \mathbf{R}(\alpha). \quad (7)$$

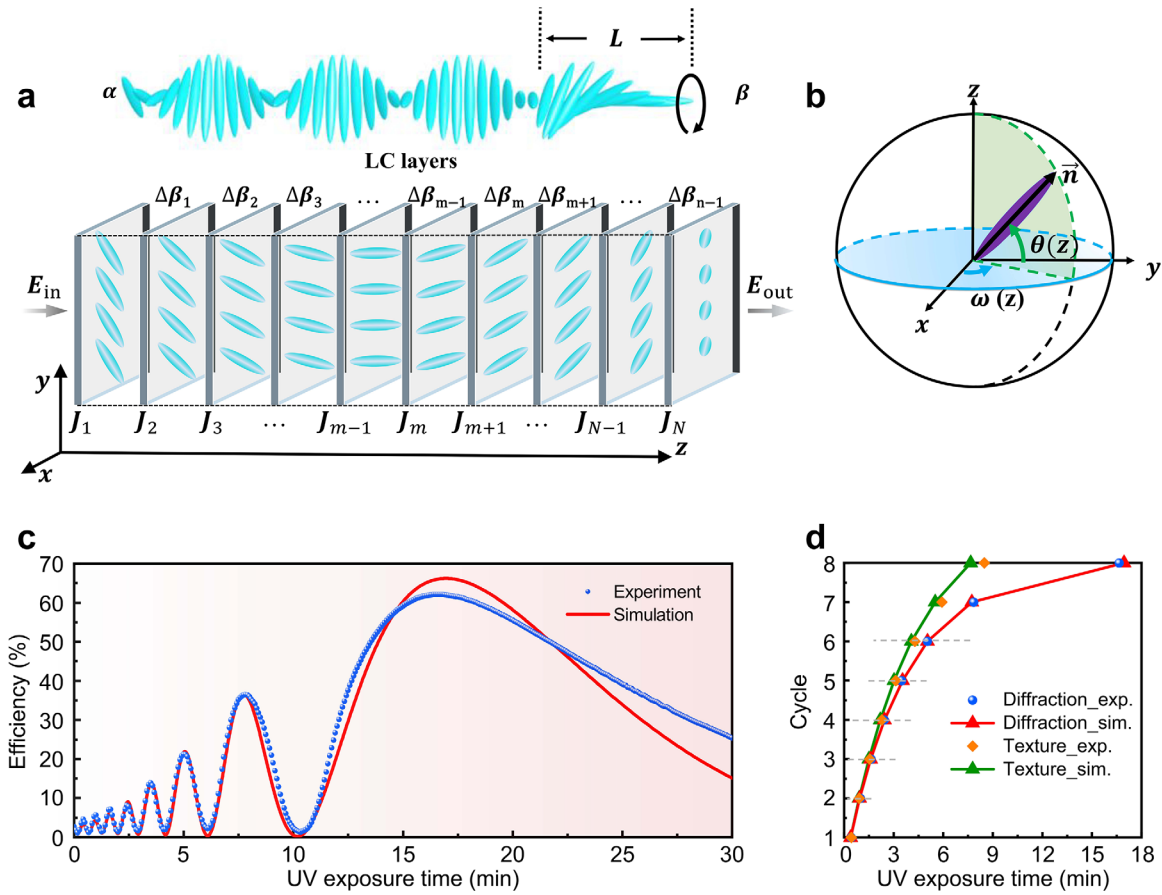


FIGURE 3 | Hybrid-anchoring model of the LC helix and fitting results. (a) Schematic illustration of the layered method used to calculate the transmission matrix of the LC element. The upper panel shows an extracted single LC helix, where α is the initial azimuthal angle, β is the total twist angle, and L is the thickness of the tilted region. The lower panel shows the discretization of the LC structure into N layers for Jones-matrix calculation, where $\Delta\beta$ denotes the incremental twist angle in each layer. (b) Schematic of the LC director. $\mathbf{n}(z)$ denotes the director of the LC molecule, $\omega(z)$ is the azimuthal angle in the $x-y$ plane, and $\theta(z)$ is the tilt angle, both varying along the thickness direction z . (c) Temporal fitting of the diffraction efficiency of PG sample. (d) Measured and fitted cycle numbers derived from the diffraction (blue and red) and the texture evolution (orange and green).

Here, $\Delta\beta_n$ is the twisting angle of the n th layer relative to the previous layer. The circular polarization basis vectors are defined as $\mathbf{e}_L = \frac{\sqrt{2}}{2} \begin{bmatrix} 1 \\ -i \end{bmatrix}$, $\mathbf{e}_R = \frac{\sqrt{2}}{2} \begin{bmatrix} 1 \\ +i \end{bmatrix}$. For LCP incident light, we adopt the Jones matrix formalism to numerically calculate the transmission process layer by layer through the whole twist structure:

$$\mathbf{E}_{out} = \mathbf{T}\mathbf{E}_{in} = \mathbf{R} \left[- \left(\alpha + \frac{2\pi D}{p} \right) \right] \prod_{n=1}^N \left(\begin{bmatrix} e^{-i\frac{\pi(n_{eff}-n_0)D}{N\lambda}} & 0 \\ 0 & e^{i\frac{\pi(n_{eff}-n_0)D}{N\lambda}} \end{bmatrix} \times \mathbf{R} \left(\frac{2\pi D}{Np} \right) \right) \mathbf{R}(\alpha) \mathbf{e}_L. \quad (8)$$

Here, D , N , λ , n_{eff} , and n_0 are all treated as constants. Therefore, the spatial distribution of the output electric field can be obtained by substituting only the azimuthal angle $\alpha(x, y)$ and the pitch $p(t)$ into the above expression. To provide a more intuitive description of the wavefront modulation mechanism, Equation (8) can be rewritten in the circular polarization basis as:

$$\mathbf{E}_{out} = C_L(\beta) \mathbf{e}_L + C_R(\beta) e^{-i2\alpha} \mathbf{e}_R. \quad (9)$$

Equation (9) explicitly shows that the wavefront is governed by the geometric phase term $e^{-i2\alpha}$, whereas the complex amplitudes $C_L(\beta)$ and $C_R(\beta)$ are determined by the twisting angle β , which is related to the pitch $p(t)$. The detailed derivation of the model and the experimentally measured pitch range are provided in Supplementary sections 1, 2 and Figure S4.

Accordingly, the diffraction efficiency η is then defined by the relative intensity of the converted orthogonal circularly polarized component:

$$\eta = \frac{I_R}{I_R + I_L} = \frac{|C_R|^2}{|C_L|^2 + |C_R|^2}, \quad (10)$$

where I_R and I_L denote the transmitted intensities of the right- and left-handed circularly polarized components extracted from $\mathbf{E}_{out}$, respectively. Using this model, we first calculate the diffraction efficiency as a function of the helical pitch p (Supplementary Figure S5). By matching the simulated diffraction efficiency with the experimentally measured temporal diffraction efficiency, the temporal evolution of the pitch is extracted and fitted as $p = 0.362 \times t^{1.025} + 1.518 \mu\text{m}$. The extracted $p(t)$ is subsequently substituted

into Equations (8) and (10) to obtain the simulated diffraction efficiency evolution shown in Figure 3c. The multi-cycle optical response arises from mapping the monotonic photoinduced pitch evolution $p(t)$ onto the non-monotonic polarization-conversion function $\eta[p(t)]$. Thus, although the molecular and helical evolutions remain monotonic, the conversion efficiency of the pre-encoded PB wavefront repeatedly passes through successive extrema, producing the observed multi-cycle temporal response. The excellent agreement with experiment demonstrates that the temporal optical response is governed by the continuous unwinding of the chiral helix under UV irradiation. Consistent temporal evolution is further evidenced by the agreement between the cycle numbers extracted from diffraction and texture dynamics, as shown in Figure 3d. The model further indicates that high polarization-conversion efficiency can be achieved through appropriate matching of the LC cell thickness and the chiral-dopant parameters (Figure S6).

2.4 | Reversible Temporal Modulation of the Fork Grating

Having established continuous UV-driven modulation, we next investigate whether the temporal response can be reversed optically, which is essential for reusable flat-optical operation. We implement an FG within the present architecture. Its initial LC director distribution is given by:

$$\alpha_{\text{FG}} = q\varphi - \frac{\pi x}{\Lambda}, \quad (11)$$

where the first term represents a q -plate and the second term represents a PG with a period of $\Lambda = 136.8 \mu\text{m}$. Figure S7 shows the phase diagram of an FG with $q = 1$. Figure 4a shows the micrograph of the fabricated FG.

We then probe its temporal response using a 633 nm LCP incident light under alternating UV and green-light irradiation. As shown in Figure 4b, the normalized intensity of the +1st-order vortex beam undergoes reversible modulation. UV irradiation at 365 nm drives pronounced oscillatory evolution of the diffracted intensity, whereas subsequent green-light irradiation at 530 nm reverses the process and restores the initial optical state. This behavior evidences reversible optical control enabled by the photoresponsive CLC medium. Complete recovery can be obtained after subsequent storage in the dark at room temperature. The corresponding diffraction patterns and optical micrographs at representative extrema are presented in Figure 4c–n. The far-field patterns show the evolution of the diffracted vortex beam, while the accompanying textures reveal the concurrent reconfiguration of the LC microstructure. To verify the orbital-angular-momentum state, we perform astigmatic transformation of the output beam. The transformed patterns, shown in the right insets of Figure 4c–n, exhibit two dark stripes, indicating $|m| = 2$, consistent with the designed $q = 1$.

2.5 | Generality of the Platform for Self-Paced Temporal Flat Optics

Finally, we demonstrate the generality of the platform by implementing several representative photopatterned geometric-phase

elements, including an axicon, an off-axis lens, and a hologram (Figure 5). These devices span canonical beam deflection, wavefront focusing, and arbitrary image reconstruction functionalities, thereby illustrating the general applicability of this approach.

As shown in Figure 5a, we first design an axicon, whose director distribution is expressed as:

$$\alpha_{\text{axicon}} = -\frac{\pi}{\Lambda} \sqrt{x^2 + y^2}, \quad (12)$$

where Λ is the radial grating period, set to $136.8 \mu\text{m}$. The fabricated sample exhibits concentric microstructural features that closely follow the designed orientation pattern (Figure 5b). Under continuous UV irradiation, the far-field diffraction does not undergo a simple on/off transition, but evolves continuously along the oscillatory trajectory schematically shown in Figure 5c. To clearly visualize this behavior, a representative interval highlighted by the blue solid segment is selected, and the corresponding diffraction patterns are presented in Figure 5d,h. The diffraction patterns in Figure 5d show that the relative intensity between the central zeroth-order spot and the outer annular diffracted field varies continuously with time. This kind of self-running response can turn the axicon into a dynamic optical warning element. Under continuous illumination at a constant UV intensity of $39.21 \mu\text{W cm}^{-2}$ (a notably low power density that underscores the sharp sensitivity of the system), the concentric ring pattern undergoes repeated bright-dark modulation with peak diffraction intensity increasing over successive cycles, giving rise to a sustained blinking behavior without any temporally varying external drive. The repeated appearance and fading of the concentric rings provide a readily recognizable visual signal of ongoing UV exposure (Supplementary Video S1), while the progressive increase in the peak intensity of successive diffraction cycles provides an additional indication of the accumulated UV dose. By reading out the brightness of the diffraction spots, one can infer how long an object, a cultural relic under conservation, for instance, has been exposed to UV light. Importantly, such a temporally structured warning response requires no externally programmed driving scheme, but instead arises from the intrinsic photoinduced evolution of the CLC itself.

As another representative device, an off-axis lens is designed in the present architecture, whose alignment orientation is expressed as follows:

$$\alpha_{\text{off-axis lens}} = -\frac{\pi x}{\Lambda} - \frac{\pi}{\lambda} \left(\sqrt{r^2 + f^2} - f \right). \quad (13)$$

The first and second terms represent the orientation introduced by the phase profiles of a PG and a lens, respectively, while Λ is set as $100 \mu\text{m}$. Here, f is the focal length, λ is the wavelength of light, and $r = \sqrt{x^2 + y^2}$ is the radial distance. To characterize the imaging performance of the off-axis lens, an experimental setup is constructed, as shown in Figure 5e. A letter “K” is placed before the off-axis lens, and the corresponding images are captured by a CCD. An off-axis lens with $f = 10.8 \text{ cm}$ at 633 nm is fabricated for demonstration. The director distributions of the off-axis lens, which combine the phase profiles of a PG and a lens, are illustrated in Figure 5f. Its microstructure, shown in Figure 5g, exhibits patterns consistent with the designed off-axis lens profile. In the

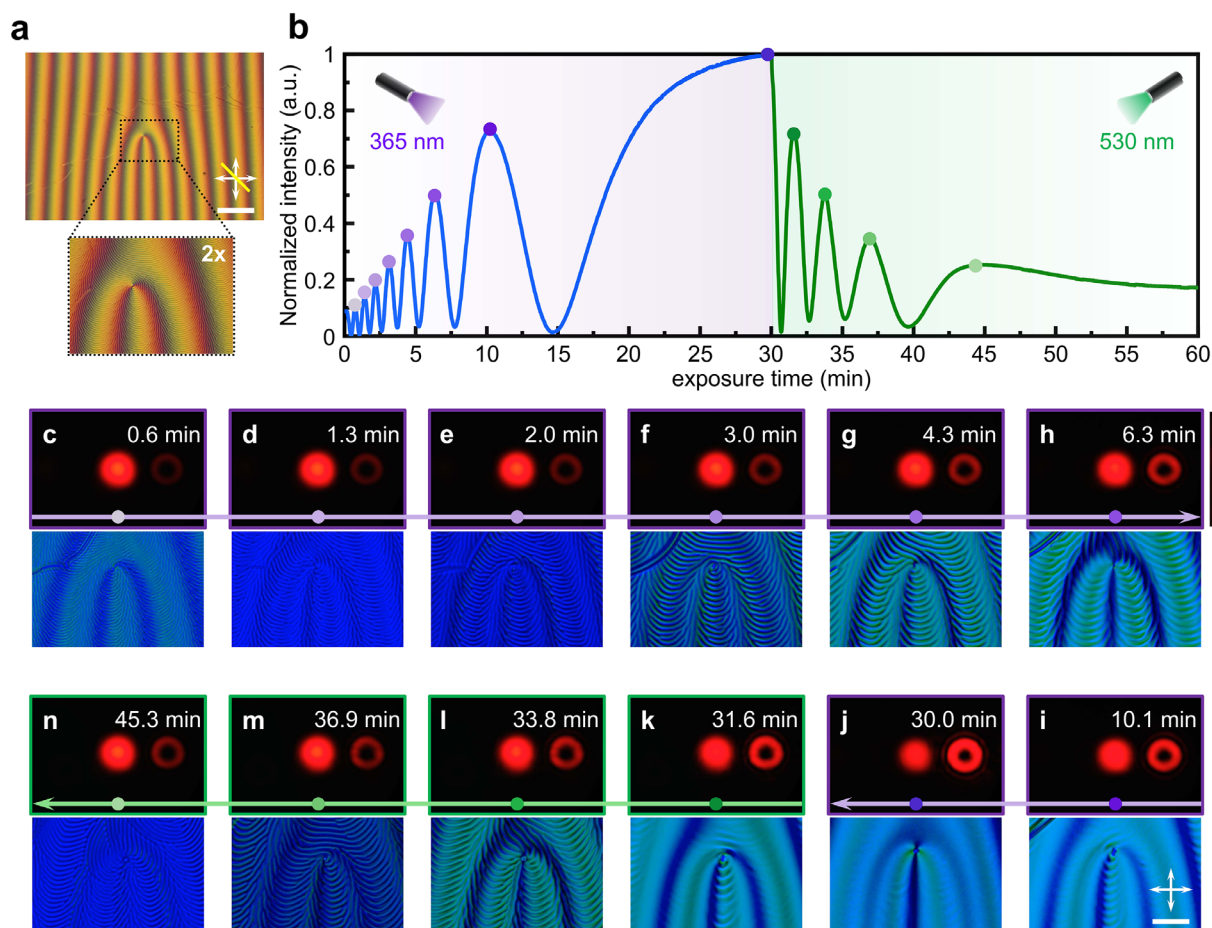


FIGURE 4 | Reversible temporal modulation of FG. (a) Microstructure image and details of the fabricated FG sample ($q = 1$). The yellow line indicates the orientation of the full-wave plate. Scale bar, 200 μm . (b) The normalized intensity of the +1st-order vortex beam is modulated reversibly under alternating UV (blue line) and green-light (green line) irradiation. The irradiation intensities of UV at 365 nm and green light at 530 nm are 40.49 and 104.15 $\mu\text{W cm}^{-2}$, respectively. (c–n) Diffraction patterns and micrographs of the FG corresponding to the different peak positions marked in (b). Scale bar, 100 μm . The right insets show the corresponding astigmatic transformation results.

imaging experiment, the object distance and image distance are set to 20 and 25 cm. The temporal imaging results of the off-axis lens are shown in Figure 5h. Due to the contribution of the PG component, the image is diffracted to a single +1st order. Upon UV irradiation, the diffracted output remains localized in the designed off-axis channel, while its intensity undergoes a clear oscillatory evolution with time. Specifically, the focused signal is initially pronounced, then gradually attenuates to a much weaker state, and subsequently recovers at later times. This result indicates that this approach can endow a compound geometric-phase element with dynamic functionality without disrupting its prescribed wavefront transformation.

To further demonstrate the generality of this approach for complex wavefront shaping, a holographic element encoding a heart-shaped image is implemented. The hologram is generated using the Gerchberg-Saxton algorithm, whose design procedure is schematically illustrated in Figure 5i. Through iterative optimization between the hologram and reconstruction planes, the phase distribution required for reconstructing the target heart-shaped image is obtained and subsequently encoded into the LC alignment field. As shown in Figure 5j, the fabricated holographic element reconstructs a well-defined heart-shaped image

whose intensity exhibits multi-cycle temporal modulation under UV irradiation. The reconstructed heart gradually fades, nearly vanishes at intermediate states, and subsequently reappears with its original geometry. The corresponding texture images recorded at representative irradiation times are provided in Figure S8. This behavior is consistent with the oscillatory optical responses observed in the axicons and off-axis lens, confirming that this approach can be extended from simple geometric-phase elements to complex holographic wavefront modulation. When integrated with an external physiological or emotion-recognition module, such a holographic element could potentially provide an intuitive visual representation of a detected state. For example, one may envision a human-machine optical interface in which a camera-based module infers a user's emotional or physiological state from subtle facial cues, and communicates that inference through switching on a constant UV illumination on a specific photopatterned LC hologram. The ensuing time-varying hologram then translates the inferred response into an immediately legible beating heart, revealing at a glance that the user is elicited by attraction or by sudden fright. Notably, in such a scheme the drive front end need only deliver an on-off trigger, while all of the temporal richness of the display is generated by the material itself. This concept suggests a potential route toward

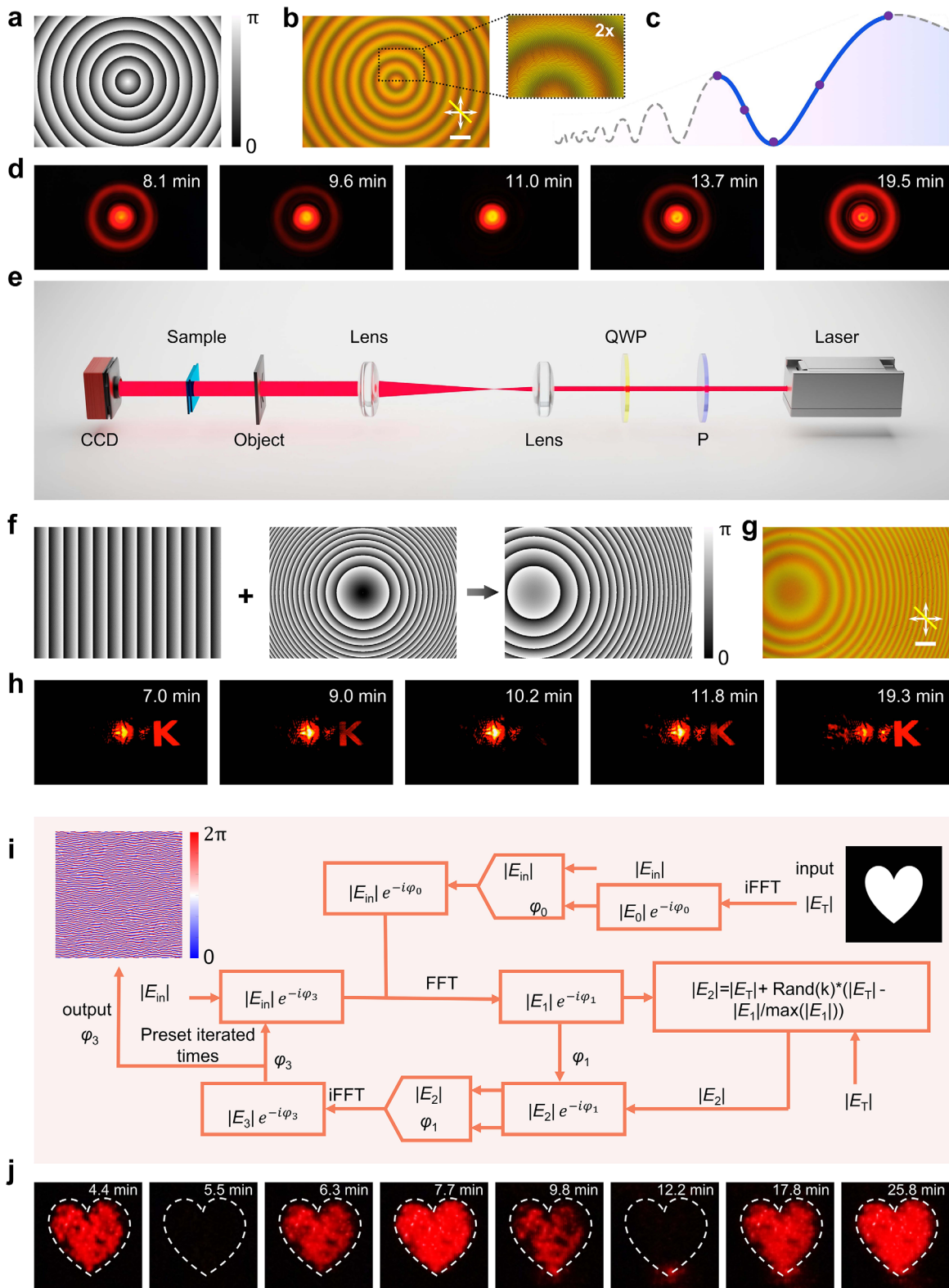


FIGURE 5 | Time-varying modulation of optical fields using photopatterned LC elements. (a) Director distribution of the axicon. (b) Microstructure image and details of the fabricated axicon sample. (c) Schematic of the oscillatory evolution of the output optical field. The gray dashed curve represents the full oscillation process, while the blue solid segment highlights the selected temporal interval. The five purple dots mark the representative time points within this interval, from which the optical outputs shown in (d) and (h) are selected. (d) Temporal evolution of axicon diffraction patterns. (e) Experimental setup for off-axis lens imaging characterization. (f) Director distributions of the off-axis lens combining a PG and a lens. (g) Microstructure image of the fabricated off-axis lens sample. (h) Temporal evolution of off-axis lens diffraction patterns. (i) Flow chart of the Gerchberg-Saxton algorithm for heart-shaped holography. (j) Temporal evolution of holograms. All scale bars are 200 μm . The irradiation intensity of UV is 39.21 $\mu\text{W cm}^{-2}$.

material-mediated visual feedback in interactive and human-machine optical interfaces.

3 | Discussion and Conclusion

In this work, we have shown that a photoresponsive CLC can supply the temporal degree of freedom of flat optics driven by a constant light stimulus. Operated in a high-twist, small-pitch hybrid-anchored geometry, the through-thickness helix winds continuously under a single, constant light stimulus, so that the conversion efficiency of a spatially pre-encoded PB wavefront oscillates through multiple cycles while the in-plane phase pattern—and hence the diffraction geometry—is preserved. For a PG, the diffraction-efficiency oscillation and the fingerprint-texture translation advance through the same number of cycles and are reproduced by a layered Jones-matrix model with a fitted pitch-time relation, consistent with the modulation arising from continuous unwinding of the hybrid-aligned helix. The temporal response is optically resettable by green light, and the same self-paced behavior carries over to FGs, axicons, off-axis lenses, and holograms. Importantly, these time-varying responses are achieved at a UV irradiance of only $\approx 40 \mu\text{W cm}^{-2}$, further establishing the platform as an electrode-free and low-irradiance route to active flat optics.

Previous studies have established the reconfigurability of hybrid-aligned CLCs, but the operating principle of our work differs from them. In the systems reported by Lin et al. and Ryabchun et al. [38, 39], diffraction originates directly from self-organized CLC stripes, whose orientation or periodicity evolves with the helical pitch under thermal, electrical, or optical stimulation. In contrast, our system functionally decouples the spatial and temporal optical responses. The photoaligned in-plane director distribution independently encodes the PB phase profile, whereas the chiral helix modulates the polarization-conversion efficiency. Although Wang et al. [31] recently demonstrated optically tunable PB PGs and geometric-phase lenses, their devices exhibited predominantly monotonic modulation of the diffraction efficiency, which is the purpose. At the same concentration of chiral dopants, the QL55 dopant used in that study [31] shows an HTP variation of approximately $12\sim 5 \mu\text{m}^{-1}$, whereas ChAD-3c-R employed here exhibits a substantially broader variation of approximately $67\sim 14 \mu\text{m}^{-1}$ under UV irradiation. This broader tuning range enables operation in a higher-twist, smaller-pitch regime and allows the continuously evolving helix to traverse multiple polarization-conversion extrema under constant UV irradiation, resulting in complex, repeated attenuation and enhancement of the pre-encoded PB optical response. Importantly, this multi-cycle behavior does not arise from the chiral dopant alone, but from the coordinated matching of its accessible pitch range with the cell thickness and intrinsic birefringence of the LC host.

Because the temporal trajectory is governed by the through-thickness chiral kinetics rather than by any particular in-plane phase profile, the same self-paced modulation should transfer to other photoaligned geometric-phase designs and, through the rich mesophase behaviors and multistimuli responsiveness of LCs, to systems driven thermally, electrically, by humidity, or mechanically and other spectral ranges; incorporating polar ferroelectric-nematic components may further open a

route toward nonlinear wavefront shaping. More broadly, by letting the material itself generate the time axis, constant-stimulus, self-paced modulation moves light-driven flat optics from a settable, externally clocked knob toward a self-clocked, time-varying primitive—an electrode-free, passively illuminated element that delivers a continuous sequence of optical states for time-multiplexed flat optics, dynamic holography, optical encryption, and dynamic imaging.

4 | Experimental Section

4.1 | Materials

The photoresponsive CLC was prepared by mixing 1.0 weight % (wt %) right-handed chiral molecular switch ChAD-3c-R (BEAM, USA) and 99.0 wt % nematic LC host E7 (Jiangsu Hecheng Display Technology Co., Ltd., China). Upon external irradiation with UV light or visible light, ChAD-3c-R undergoes trans-cis photoisomerization, leading to a continuous increase or decrease in the helical pitch of the system. A polarization-sensitive sulfonic azo dye SD1 (Dai-Nippon Ink and Chemicals, Japan) was dissolved in N,N'-dimethylformamide at a concentration of 0.8 wt % and then spin-coated as a planar alignment layer, of which the molecular structure is shown in Figure S1a–c. SD1 molecules are sensitive to the polarization of incident light. After absorbing UV photons, the dye molecules isomerize and finally tend to orientate perpendicularly to the local polarization because of their dichroic absorptions. Only the last photo-reorientation will be recorded. A polyimide solution ZKPI-4070 (POME Technology Co., Ltd., China) was employed for the homeotropic alignment layer at the other substrate. Such material was stable with respect to UV and visible irradiation.

4.2 | Fabrication

An indium-tin-oxide (ITO) glass substrate was first cleaned using UV-ozone treatment and then spin-coated with a photoalignment agent (SD1) at two sequential stages: 800 rpm for 10 s, followed by 3000 rpm for 40 s. The coated substrate was then cured at 100°C for 10 min to ensure proper cross-linking of the photoalignment layer. Then, the ZKPI-4070 alignment layer was prepared by spin coating onto the other substrate at three sequential stages: 300 rpm for 10 s, followed by 8000 rpm for 40 s, and finally, 100 rpm for 3 s. The spin-coated glass was first preheated at 80°C for 5 min and then baked at 230°C for 30 min. Subsequently, the prepared planar aligned substrate and the homeotropic aligned (ZKPI-4070) substrate were separated by $9 \mu\text{m}$ spacers and sealed with epoxy glue to form a cell (Figure S1d).

Then the empty LC cell was placed at the image plane of the digital micromirror device (DMD)-based UV microlithography system to record the patterns of LC director distribution via a multistep partly overlapping exposure process with a synchronous polarization control (Figure S1e). Finally, the photoresponsive CLC mixture was injected into the cell by capillary action at $\sim 70^\circ\text{C}$, and was slowly cooled to room temperature after the LC infiltration process was complete. The photoalignment process is more efficient when the temperature is at 25°C and the humidity

is <40%. Thereafter, a hybrid-aligned and photopatterned photoresponsive liquid crystal system was thereby obtained.

4.3 | Characterizations

All experiments were conducted at room temperature under ambient environment. The textures of photopatterned CLCs were obtained by a crossed polarizing optical microscope (DM2700P, Leica). The LC samples were excited with a 633 nm laser (TEM-F-633, Changchun New Industries Optoelectronics Technology Co., Ltd., China), and the polarization state of the incident light was adjusted using a quarter-wave plate (AWP20Q-T2Q, JCOPTIX, China). The light exposure process was carried out using a 365 nm UV light-emitting-diode (LED) source (M365L3, Thorlabs) and a 530 nm green LED source (M530L4, Thorlabs). In all optical measurements, the 633 nm probe light was normally incident from the photopatterned planar-alignment side (SD1 coated substrate).

Author Contributions

L.-L.M., Y.-Q.L., X.-H.L. and Z.-Y.W. conceived the design of this work. X.-H.L., Z.-Y.W., and L.-L.M. established the LC theoretical model and performed the experiments; L.-L.M. and Y.-Q.L. directed and supervised the research. X.-H.L., Z.-Y.W., L.-L.M., D.L., and Y.-Q.L. contributed to the data analysis. X.-H.L., Z.-Y.W., and L.-L.M. prepared the manuscripts; L.-L.M., X.-H.L., Z.-Y.W., D.L., L.-Y.W., Y.W., J.-T.P., R.Z., and Y.-Q.L. revised the manuscripts; all authors discussed the results and commented on the manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

All data needed to evaluate the conclusions in the paper are presented in the paper. Additional data related to this paper may be requested from the authors.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supporting File 1: adfm78842-sup-0001-SuppMat.docx.

Supporting File 2: adfm78842-sup-0002-VideoS1.mp4.