

RESEARCH ARTICLE

High-Speed Electrically Driven Liquid-Crystal Compact Optical Skyrmion Encoder

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ABSTRACT

Optical skyrmions are topologically nontrivial polarization textures with intrinsic robustness under external perturbations, making them promising carriers for disturbance-resistant optical information transmission. However, existing optical skyrmion generation schemes mostly rely on static optical devices or fixed nanostructures, making high-speed dynamic switching of the topological state difficult. Here, we propose a high-speed switchable optical skyrmion encoder based on a compact liquid-crystal spin-orbit device. The device employs the in-plane orientation of liquid crystal molecules to imprint a fixed Pancharatnam-Berry geometric phase, while an applied voltage rapidly tunes the liquid-crystal retardance. This electrical control enables reversible switching of the output state from a skyrmionic polarization texture to a uniformly polarized vortex and vice versa. Experimental results show that the device exhibits millisecond electrical response, with bidirectional response times of 1.76 and 0.72 ms, corresponding to an ideal cycling rate of approximately 403 Hz, making it the fastest switchable optical skyrmion generator to date, to the best of our knowledge. Furthermore, by exploiting this rapid topological refreshing capability, we demonstrate image encoding and decoding, providing a new liquid-crystal device platform for high-speed, refreshable, and disturbance-resistant topological optical information transmission.

1 | Introduction

Skyrmions are topologically protected quasiparticles initially proposed in condensed-matter physics that have attracted broad interest across diverse photonic systems [1–7]. In optical systems, the rich degrees of freedom of light provide a versatile platform for constructing skyrmion mappings. By engineering Stokes parameters [8–11], electromagnetic field vectors [12, 13], spin angular momentum [14–17], and momentum-space pseudospin vectors [18–20], optical skyrmions have been generated and manipulated

in multidimensional photonic parameter spaces. Among these implementations, Stokes skyrmions are particularly attractive because the spatial distribution of polarization states can be directly mapped onto the Poincaré sphere, allowing the skyrmion number N_{sk} to serve as a measurable topological index for robust optical encoding [21–23]. Such topological structures can maintain distinguishable information under perturbations such as turbulence [24–26], scattering, and noise [27], making them promising carriers for disturbance-resistant optical information transmission [26].

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Despite these prospects, most existing optical skyrmion encoding schemes remain essentially static. Free-space interferometric systems and spatial-light-modulator-based approaches can flexibly synthesize skyrmionic polarization textures [28, 29], but they are usually bulky and not well suited for compact high-speed modulation. Metasurfaces [30–32] and integrated photonic platforms have greatly reduced the device footprint and enabled complex spin-orbit transformations in planar or on-chip structures [33–35]. However, the generated skyrmion state is often fixed by a predefined device structure, making high-speed topological switching a key challenge for practical information applications [36, 37]. Liquid crystals offer a promising route to electrically switchable optical skyrmion generation by combining spatially patterned spin-orbit coupling with voltage tunability [38–41]. In a Pancharatnam-Berry spin-orbit device, the written liquid-crystal orientation defines a fixed geometric-phase channel, whereas the electrically controlled retardance tunes the modal balance between Gaussian and vortex components. This enables rapid switching of the output Stokes texture between skyrmion and non-skyrmion states without rewriting the spatial pattern. This capability makes our proposed liquid-crystal platform particularly suitable for compact, electrically addressable and refreshable optical skyrmion systems.

Here we implement this concept using a patterned liquid-crystal spin-orbit device, in which the written director field defines a fixed Pancharatnam-Berry phase and the applied voltage tunes the retardance. At 633 nm, voltage-controlled Gaussian-vortex modal balancing drives the reconstructed Stokes texture to rapidly switch between skyrmion and non-skyrmion states. The device exhibits millisecond-scale bidirectional electrical switching, with characteristic response times of 1.76 and 0.72 ms, corresponding to an ideal bidirectional cycling rate of approximately 403 Hz. To the best of our knowledge, this represents the fastest switchable optical skyrmion encoder reported to date [42–44]. Skyrmion generation is maintained over most operating voltages and remains stable for 10^4 s under continuous bias, demonstrating robust voltage-addressed topological control. We further demonstrate the generation of a second-order skyrmion texture and exploit the electrically refreshed topological contrast to realize encoding and decoding of a 16×16 , 256-bit image. These results pave the way for high-speed, disturbance-resistant optical information transmission based on dynamically refreshable skyrmion states.

2 | Results

2.1 | Voltage-Addressed Topological Evolution

Liquid crystals are self-organized anisotropic soft materials that combine spatially programmable molecular alignment with pronounced electro-optic responsiveness [45–47]. This dual capability allows a single patterned layer to encode a prescribed geometric-phase transformation while retaining dynamic control over the spin-orbit conversion. In the present device, these two degrees of freedom are assigned distinct roles. The patterned in-plane director field $\alpha(x, y)$ fixes the local optical-axis orientation and the associated Pancharatnam-Berry phase (Figure 1a,b), thereby defining the spatial spin-orbit channel [48]. By contrast, the applied voltage induces out-of-plane director reorientation

through the cell thickness and changes the effective birefringence and retardance without rewriting the in-plane pattern (Figure 1c). Electrical addressing therefore controls the polarization conversion efficiency while preserving the encoded spatial phase profile [38, 39, 45].

$$\delta(V, d, \lambda) = \frac{2\pi}{\lambda} \Delta n_{\text{eff}}(V) d \quad (1)$$

Here, d is the cell thickness, λ is the operating wavelength, and $\Delta n_{\text{eff}}(V)$ is the voltage-dependent effective birefringence. Equation (1) defines the electrical control coordinate: voltage changes the retardance without rewriting the patterned geometric-phase channel [45]. The corresponding one-dimensional electro-optic model is provided in Note S1.

For the fixed incident circular polarization $|\sigma_0\rangle$, used in the experiments, the field at the selected observation plane can be written as,

$$E_{\text{out}}(r, \phi, V) = \cos\left[\frac{\delta(V)}{2}\right] u_G(r) |\sigma_0\rangle + i \sin\left[\frac{\delta(V)}{2}\right] u_L(r) e^{il\phi} |-\sigma_0\rangle \quad (2)$$

Here, the first and second terms denote the co-polarized and cross-polarized output fields. $u_G(r)$ and $u_L(r)e^{il\phi}$ are their respective spatial profiles after propagation to the observation plane, and l is the azimuthal order whose sign depends on the helicity of the input polarization. Since the birefringence is uniform along the liquid-crystal device, the co-polarized wave has the same spatial profile as the input beam (Gaussian). On the other hand, the cross-polarized wave exhibits a standard vortex profile due to the written geometric phase $2\sigma_0\alpha(x, y) = l\phi$. Equation (2) makes the control mechanism explicit: the patterned director field fixes the vortex phase [45], whereas $\delta(V)$ controls the modal weights through $a_G(V) \propto \cos[\frac{\delta(V)}{2}]$, $a_L(V) \propto \sin[\frac{\delta(V)}{2}]$ [49, 50]. The characteristic skyrmion size can be shrunk to arbitrary small scales by reducing the weight of the Gaussian component, in this case the co-polarized wave. This Gaussian-vortex redistribution forms the operating pathway in Figure 1d and is measured through the two circular-polarization channels in Figure 2. Defining $A_G(r, V) = a_G(V)u_G(r)$ and $A_L(r, \phi, V) = a_L(V)u_L(r)e^{il\phi}$, the normalized Stokes components in the ordered circular-polarization basis ($|\sigma_0\rangle, |-\sigma_0\rangle$) are

$$s_3 = \frac{|A_G|^2 - |A_L|^2}{|A_G|^2 + |A_L|^2}, \quad s_1 + i s_2 = \frac{2A_G^* A_L}{|A_G|^2 + |A_L|^2} \quad (3)$$

The local modal ratio in Equation (3) determines the radial variation of s_3 , whereas the coherent cross term carries the azimuthal winding of the transverse Stokes field [30], with $\arg(s_1 + i s_2) = \text{atan2}(s_2, s_1)$ giving the corresponding azimuth on the Poincaré sphere. This winding is inherited from the vortex phase $e^{il\phi}$ in Equation (2). For $|l| = 1$, the transverse Stokes field therefore covers the azimuthal direction once while s_3 spans the polar direction, forming a first-order Stokes skyrmion [50].

Near the half-wave condition $\delta = \pi$, the co-polarized wave vanishes, and the output wave is simply a circularly polarized

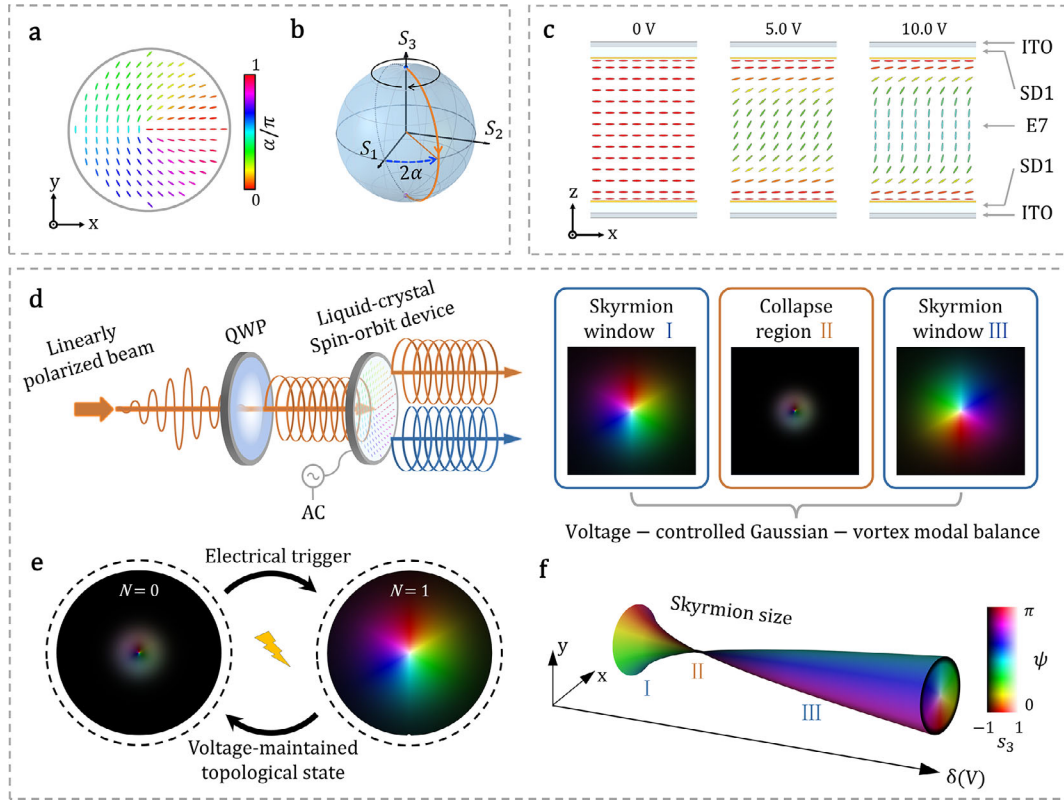


FIGURE 1 | Concept and control pathway of the voltage-addressed optical-skyrmion state encoder. (a) Patterned in-plane liquid-crystal director field $\alpha(x, y)$, which defines the fixed spatial Pancharatan-Berry geometric phase. (b) Geometric-phase-mediated spin-orbit conversion on the Poincaré sphere. The local optical-axis orientation introduces a spin-dependent phase $2\sigma\alpha(x, y)$ in the cross-polarized wave. (c) Voltage-induced reorientation of the liquid-crystal directors. The applied alternating-current (AC) voltage reduces the effective birefringence thereby tuning the retardance $\delta(V)$ without rewriting the in-plane director pattern. (d) Operating principle of the voltage-addressed optical-skyrmion generator. Voltage-controlled retardance changes the relative weight between the Gaussian-like (co-polarized) and vortex-like (cross-polarized) components, producing, within the selected branch surrounding the half-wave condition, two skyrmion windows with $N_{sk} \approx 1$ separated by a collapse region where the co-polarized wave is negligible and only a cross-polarized vortex is observed ($N_{sk} \approx 0$). (e) Conceptual electrical addressing between a vortex-like ($N_{sk} \approx 0$) state and a skyrmion state ($N_{sk} \approx 1$) under the corresponding applied bias. (f) Evolution of the characteristic skyrmion size as the Gaussian-vortex modal balance varies.

vortex beam with opposite helicity, as shown in Figure 1e. Away from this condition, the co-polarized (Gaussian-like) component reappears and the skyrmionic texture is restored [28, 37].

The effective birefringence is tuned by the voltage, which ultimately controls the characteristic skyrmion size [50], as depicted in Figure 1f. Within the experimentally selected retardance branch surrounding the half-wave condition, the model therefore predicts a reversible $N_{sk} \approx 1 \rightarrow 0 \rightarrow 1$ trajectory, accompanied by contraction and recovery of the skyrmion-density support and sign reversal of s_1 and s_2 . These predictions are tested through the voltage-retardance calibration and Stokes reconstruction in Figures 2 and 3.

2.2 | Experimental Validation of Voltage-Addressed Optical-Skyrmion Switching

Guided by this picture, we first calibrated how the patterned liquid-crystal device converts voltage into spin-orbit modal redistribution. Crossed-polarizer microscopy revealed the characteristic rotational texture across the device aperture (Figure 2a). Although the applied voltage continuously modified the color

and intensity of the observed pattern, the characteristic azimuthal symmetry of the written texture remained discernible throughout the voltage scan. These changes arise from the field-induced reduction of the effective birefringence of the E7 layer and the corresponding variation in optical retardance [46].

The voltage-dependent spin-orbit conversion was resolved in the circular-polarization basis. The co-polarized channel contained the unconverted Gaussian-like component, whereas the cross-polarized channel carried the geometric-phase vortex-like component [39, 40, 45]. The normalized profiles are shown as slice plots ($x = 0$) for 4.4, 5.0, and 7.6 V, showing the co-polarized and cross-polarized waves, the former vanishing approximately near 5.0 V (Figure 2b). Their powers (integrated intensity profiles) further quantify the voltage-dependent polarization conversion efficiency (Figure 2c).

In the ideal lossless-retarder approximation, the polarization conversion efficiency can be estimated as

$$F_{-\sigma}(V) \approx \sin^2 \left[\frac{\delta(V)}{2} \right] \quad (4)$$

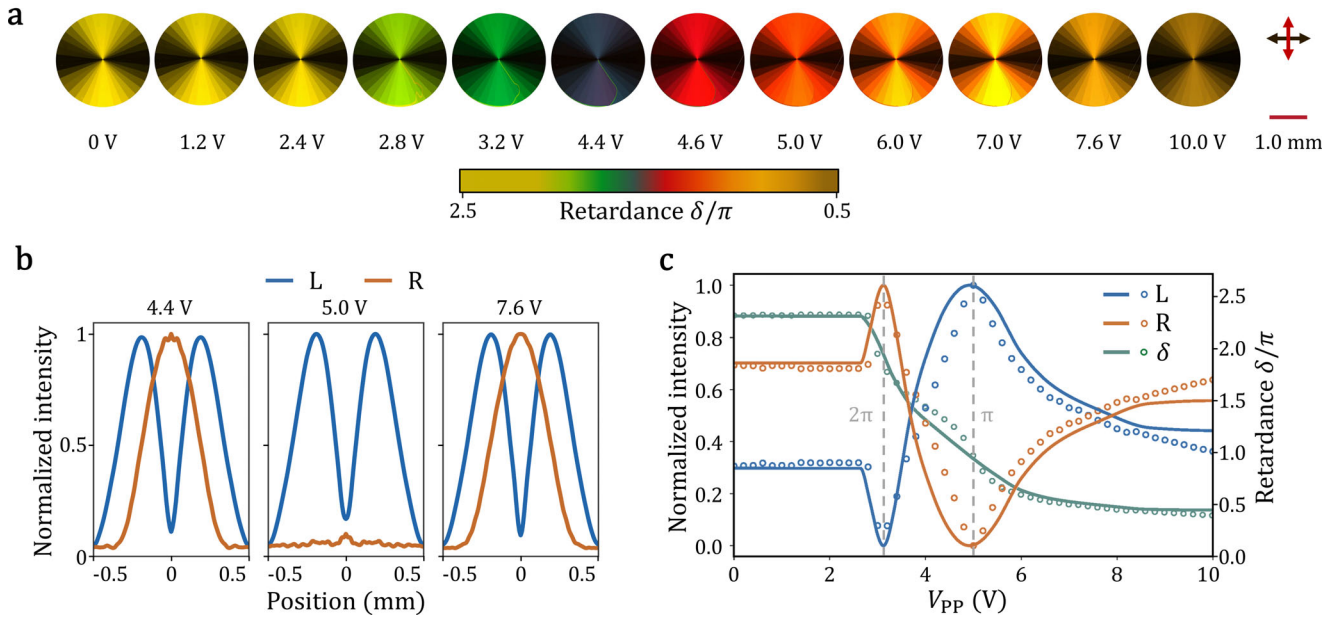


FIGURE 2 | Patterned director field and voltage-retardance calibration. (a) Cross-polarized micrographs of the patterned liquid-crystal spin-orbit device under different driving voltages, showing the written rotational director field and its voltage-dependent retardance response. The color contrast arises from voltage-tuned birefringent retardance under crossed polarizers, and the overlaid scale indicates the model-calibrated phase delay at 633 nm. Scale bar, 1.0 mm. (b) Normalized slice plots of the two circular-polarization channels at representative voltages, identifying the co-polarized (Gaussian-like), and cross-polarized (vortex-like) components. (c) Relative powers (integral of the intensity) and inferred retardance $\delta(V)$, showing the voltage-dependent polarization conversion efficiency. Open circles denote experimental data, solid lines are fits to the experimental data, and gray dashed lines mark the $\delta \approx 2\pi$ and $\delta \approx \pi$ coordinates.

because the conversion fraction is periodic in δ , the physical retardance branch was determined from the continuity of the voltage scan, the independently estimated initial retardance, and the monotonic decrease in effective birefringence under increasing voltage. The inferred retardance decreased continuously with voltage and passed through the half-wave condition near the maximum of the vortex-like output (Figure 2c). This voltage-retardance calibration was subsequently used to track the topological evolution of the reconstructed Stokes field.

Guided by the calibrated voltage-retardance relation, we performed voltage-resolved Stokes polarimetry at 633 nm to test the predicted window-collapse-window transition across the half-wave condition. The normalized Stokes vector was obtained from six polarization-resolved intensity measurements, and the skyrmion number was calculated within a finite region of interest defined with an active contour model, as described in Methods. In skyrmion window I, N_{sk} remains close to unity. It then decreased sharply to nearly zero around 5.0 V since the polarization texture shrank to an extremely small size and its topological index could not be recovered from the experimental data, yielding $N_{sk} \approx 0$. Then the skyrmion size increases again yielding a near-integer plateau in skyrmion window III (Figure 3a,b). The voltage scan thus produced a clear $N_{sk} \approx 1 \rightarrow 0 \rightarrow 1$ evolution.

Representative measurements illustrate this evolution in greater detail (Figure 3c and Figure S2). At 3.6 and 4.4 V, the textures exhibit a continuous azimuthal winding and yield $N_{sk} = 0.997$ and 0.987, respectively. Near 5.0 V, the co-polarized wave is so weak that it is not possible to recover the polarization texture, and N_{sk} approaches zero. At 5.4, 7.6, and 10.0 V, the skyrmionic texture

was progressively restored, with corresponding N_{sk} of 0.915, 0.944, and 0.997.

The component-resolved Stokes maps reveal an additional symmetry across the collapse region (Figure 3d). The spatial distributions of s_1 and s_2 on the two sides of the half-wave condition had opposite signs, whereas the characteristic core-ring distribution of s_3 was largely preserved. This sign reversal corresponds to a π rotation of the transverse Stokes texture about the s_3 axis. Near 5.0 V, s_1 and s_2 were strongly suppressed, and the reconstructed field no longer covered the Poincaré sphere completely. At higher voltages, the transverse components reappeared with the opposite orientation, accompanied by the recovery of the skyrmion number. These observations are consistent with the voltage-controlled Gaussian-vortex modal-balance picture developed above. An animated voltage-resolved sequence assembled from the reconstructed Stokes textures at each measured voltage visualizes the contraction, collapse and recovery of the first-order skyrmion texture (Movie S1).

Having established voltage-selective switching between skyrmionic texture and uniformly polarized vortex states, we next examined whether an electrically addressed skyrmion state can be held stably under continuous bias. Under continuous driving at 7.6 V_{PP} and 10 kHz, N_{sk} remained on a stable near-unity plateau over 10^4 s (Figure 4a). The reconstructed textures recorded at 0, 10^2 and 10^4 s gave $N_{sk} = 0.955$, 0.957, and 0.956, respectively. The corresponding s_1 , s_2 and s_3 maps were also nearly unchanged over the same interval (Figure 4b). These measurements show that the selected skyrmion state remains stable under continuous electrical driving (Figure S3).

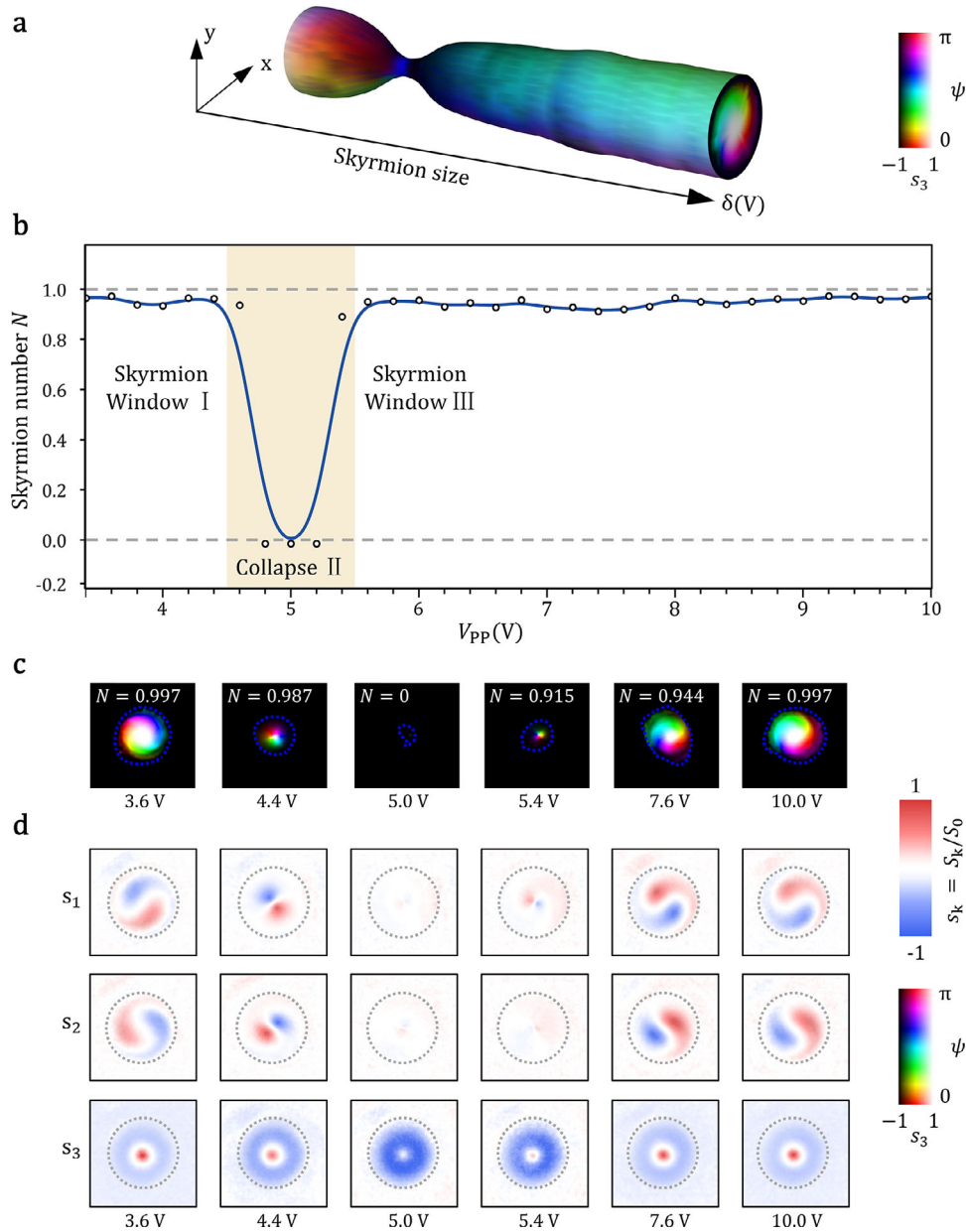


FIGURE 3 | Voltage-defined skyrmion windows and reversible topological collapse at 633 nm. (a) Experimental Stokes textures under different driving voltages, showing the contraction and re-expansion of the effective skyrmion size. Hue denotes the local polarization azimuth $\psi = 1/2 \arg(s_1 + i s_2)$, and brightness denotes s_3 . (b) Measured N_{sk} as a function of voltage. Points denote experimental values, the solid lines are fits to the experimental data, and the shaded region marks collapse region II between skyrmion windows I and III. (c) Representative Stokes textures at selected voltages, inset shows the measured N_{sk} . Blue dotted contours indicate the skyrmion boundary used for N_{sk} integration. (d) Normalized Stokes components s_1 , s_2 and s_3 at the same voltages, showing sign reversal of s_1 and s_2 across the half-wave condition while the s_3 core-ring structure is largely retained.

Beyond the long-term holding of an addressed skyrmion state, we next examine whether the same retardance-controlled mechanism extends to a higher-order texture [36, 37, 42]. An independently fabricated second-order liquid-crystal spin-orbit device exhibits the same window-collapse-window evolution: two voltage windows with N_{sk} close to -2 are separated by a near-zero-topology collapse region (Figure 4c). In the two operating windows, the measured skyrmion number remains near -2 , whereas around the collapse voltage the polarization texture becomes again impossible to reconstruct from experimental data.

Representative textures at 4.0 and 8.8 V show the expected double azimuthal winding, with $N_{sk} = -1.925$ and -1.961 , respectively, while the texture at 5.6 V collapsed into a vortex beam with circular polarization (Figure 4d and Figure S4). The negative sign follows the adopted helicity and coordinate convention for the Stokes-vector integration. Therefore, the voltage-addressed skyrmion-window response can be easily extended from the first-order to high-order textures. An analogous animated voltage-resolved sequence assembled from the reconstructed second-order textures at each measured voltage is provided in Movie S2.

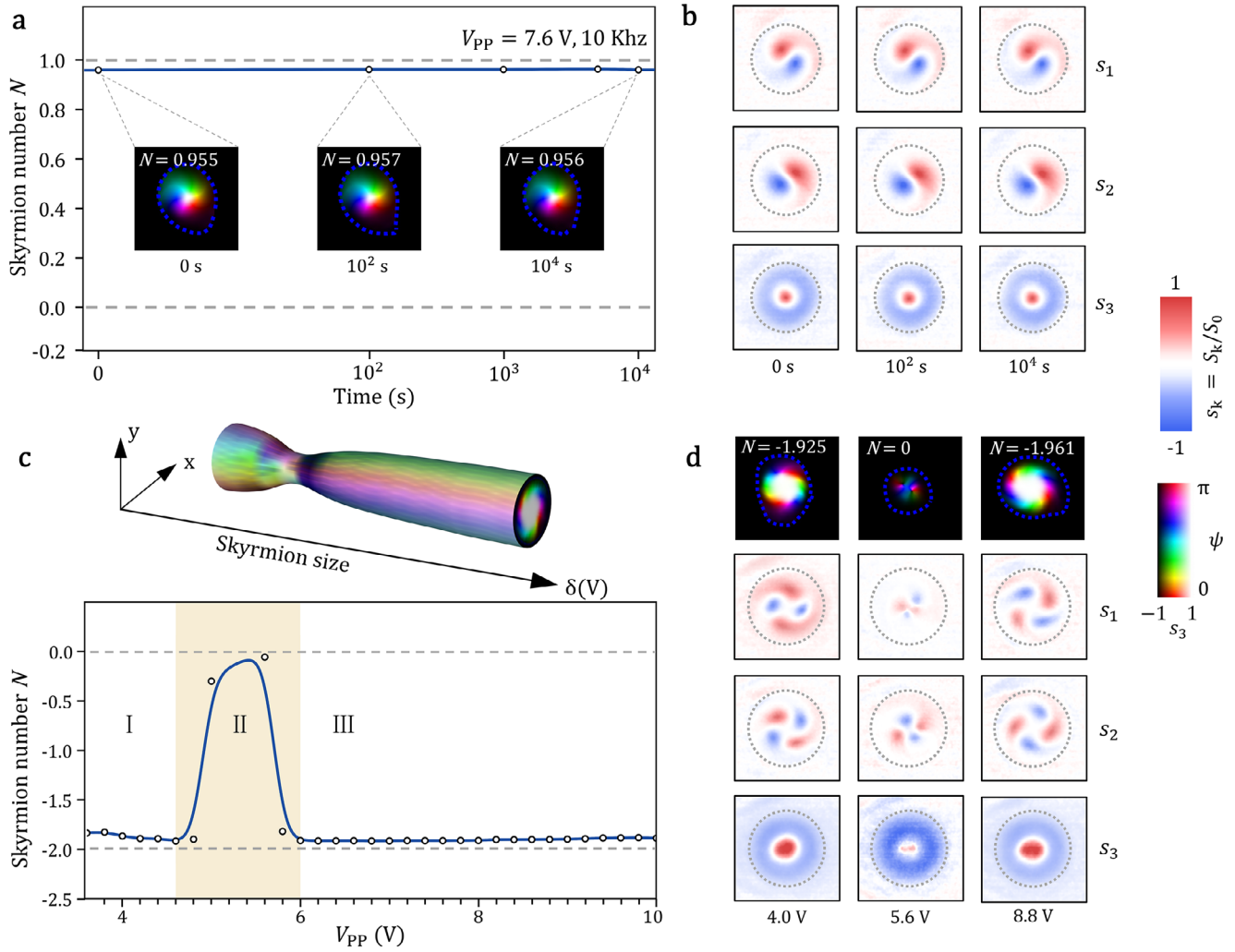


FIGURE 4 | Voltage-maintained skyrmion holding and second-order topological extension. (a) Long-time evolution of N_{sk} under a fixed driving voltage. Insets show representative skyrmion textures at $t = 0, 10^2$ and 10^4 s, with the corresponding N_{sk} values. (b) Normalized Stokes components s_1, s_2 , and s_3 at the same times, showing preservation of the addressed texture under continuous bias. (c) Voltage response of a second-order optical skyrmion device, with N_{sk} remaining close to -2 in skyrmion windows I and III and decreasing to near zero in collapse region II. (d) Representative second-order Stokes textures and corresponding normalized Stokes components at selected voltages.

2.3 | Electrically Refreshed Topological-State Encoding and Image Reconstruction

We next used the voltage-addressed vortex-skyrmion transition to demonstrate a dynamically refreshed topological-state information alphabet. A first-order device with a zero-voltage retardance close to the half-wave condition was selected for this experiment. At 0 V, the polarization conversion approaches 100%, so the output is dominated by the vortex-like component, and the skyrmion number drops to zero. At 4 V, the co-polarized wave (Gaussian-like) reappears and the resulting polarization field is a first-order skyrmion. Time-resolved intensity measurements in the helicity-flipped channel, opposite to the incident circular polarization, quantified the electrical switching dynamics between the two voltage-selected topological states (Figure 5a).

To determine the refresh rate of this topological alphabet, we measured the electrical switching dynamics between the calibrated logic states [45] (Figure 5b). The transient response was recorded through the normalized optical signal R_{norm} in the

polarization channel providing the highest contrast between the two calibrated states. Repeated switching between 0 and 4 V produced reproducible transitions between two stable optical levels. The 10%–90% response times were 0.72 ms for the vortex-to-skyrmion transition and 1.76 ms for the reverse transition. Their combined response time of approximately 2.48 ms corresponds to a response-time-derived upper cycling rate of about 403 Hz. Detailed definitions of the rise/fall times are provided in Methods, and the voltage-dependent transients and repeated-cycle statistics are shown in Figure S5.

The clear optical contrast and millisecond switching speed then allowed the two voltage-addressed states to be used as binary topological symbols (Figure 5c). The vortex-like state at 0 V represented logic 0, while the skyrmion state at 4 V represented logic 1. A 16×16 binary target image was rasterized into a 256-bit sequence and converted into the corresponding electrical waveform (Figure 5d,e). During serial driving, R_{norm} followed the programmed voltage sequence between the two calibrated levels, retaining a clear optical contrast throughout

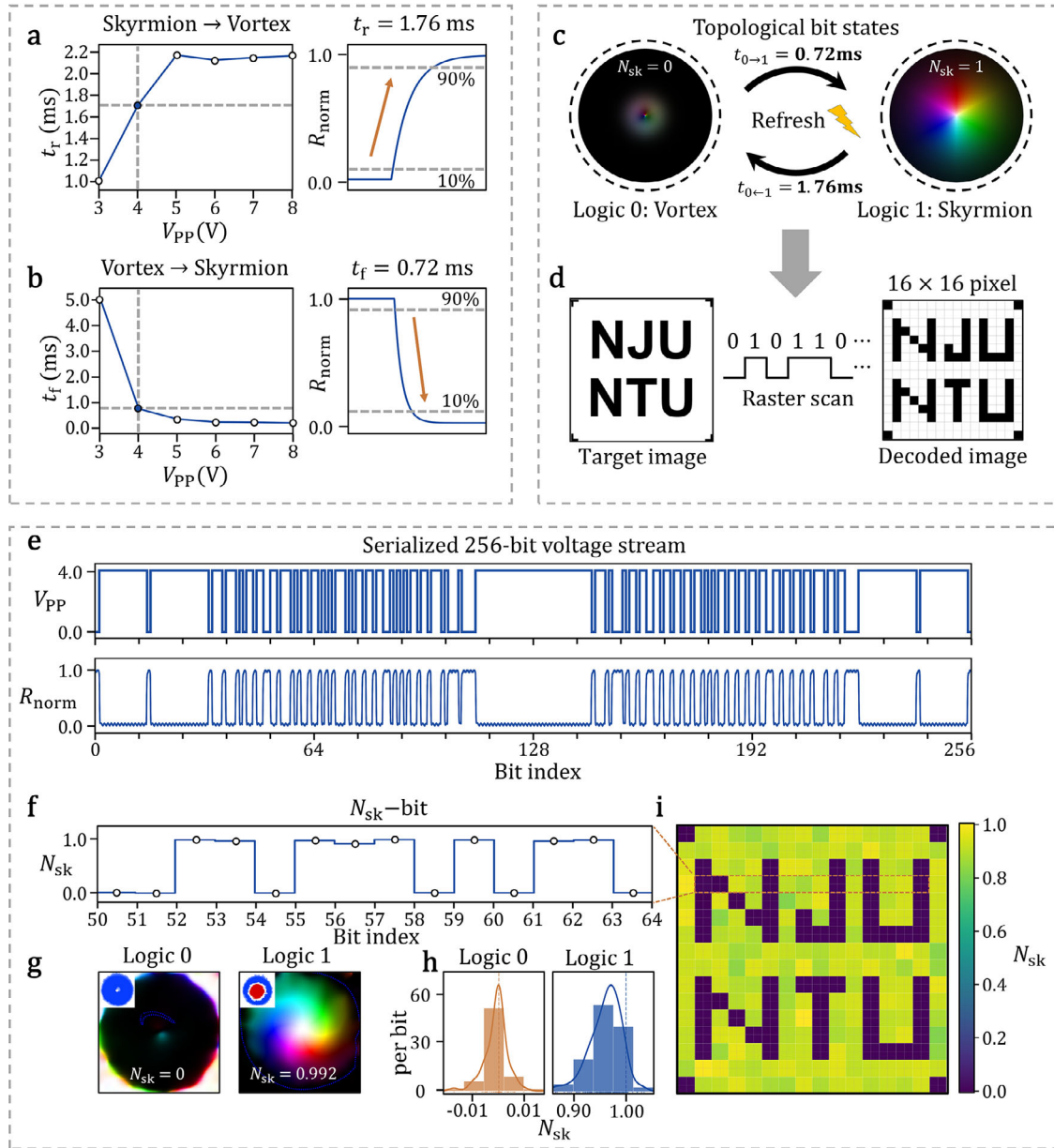


FIGURE 5 | Electrically refreshed topological bit encoding and 256-bit image reconstruction. (a,b) Bidirectional electrical switching between vortex-like and skyrmion states. The normalized readout signal R_{norm} reports the millisecond optical transient, with characteristic times of 1.76 ms for skyrmion to vortex switching and 0.72 ms for vortex to skyrmion switching. (c) Binary topological-state definition, assigning the vortex-like state to logic 0 and the skyrmion state to logic 1. (d) Conversion of a 16 × 16 binary target image into a 256-bit raster-scanned sequence. (e) Serial 0/4 V driving waveform and corresponding R_{norm} response. (f) N_{sk} readout over a representative local bit interval. (g) Representative reconstructed textures for logic 0 and logic 1. (h) Distribution of measured N_{sk} values for the two logic states, showing clear binary separation. (i) 16 × 16 image reconstructed from the measured N_{sk} values.

the complete bit stream. The time-resolved signal was recorded in the selected polarization channel to characterize the optical switching dynamics.

To characterize the topological states of the encoded sequence, six polarization-resolved intensity images (I_H , I_V , I_D , I_A , I_R , and I_L) were recorded at each of the 256 bit positions, from which the corresponding Stokes textures and N_{sk} values were reconstructed. Within a representative segment of the sequence, the measured N_{sk} values alternated between near-zero and near-unity levels in agreement with the programmed binary data (Figure 5f). The corresponding reconstructed textures displayed the expected

vortex-like and skyrmion polarization distributions (Figure 5g). Across the full sequence, the measured states formed two well-separated N_{sk} distributions associated with logic 0 and logic 1 (Figure 5h). The complete 16 × 16 set of reconstructed Stokes textures is provided in Figure S8.

The decoded topological states were finally rearranged according to the original raster order. The reconstructed 16 × 16 pattern reproduced the target image (Figure 5i), completing the sequence from electrical waveform generation and topological-state writing to polarization-resolved readout and image recovery. The progressive bit-by-bit reconstruction of the 256-bit image from the serial

topological readout is shown in Movie S3. These results demonstrate that the electrically refreshed vortex-skyrmion contrast can serve as a dynamically addressable topological information alphabet.

3 | Discussion

The main advance of this work is the separation of static spatial phase encoding from dynamic modal-balance control in a compact liquid-crystal spin-orbit device. This control scheme complements SLM-based free-space approaches [28, 29], meta-surface [30, 33], and detuned-q-plate approaches [40], which offer different trade-offs in optical alignment, structural compactness, and reconfigurability. In the present platform, the fixed in-plane director field preserves the Pancharatnam-Berry phase channel, whereas the electrically tuned retardance controls the modal balance between the co-polarized (Gaussian-like) and cross-polarized (vortex-like) components. This design allows the reconstructed optical skyrmion state to be electrically refreshed without rewriting the patterned spatial phase profile, and reveals a voltage-addressed window-collapse-window pathway in which the Stokes texture reversibly switches between near-integer skyrmion states and a vortex-dominated near-zero-topology collapse state. By exploiting this millisecond vortex-skyrmion switching contrast as a binary topological alphabet, we further demonstrate a 256-bit serial state-writing and polarization-resolved image-reconstruction workflow. These results advance optical-skyrmion state generation from static-state preparation toward electrically refreshable topological-state modulation in a compact liquid-crystal platform. Future system-level implementation may require faster liquid-crystal materials, thinner cells, parallel Stokes readout, and array-addressed device architectures to close the gap between electrical writing, topological-state identification, and information throughput. In particular, emerging ferroelectric nematic liquid crystals provide a promising route toward much faster electro-optic response [51]. Integrating fast liquid-crystal materials with patterned spin-orbit devices may further extend the present platform from millisecond topological refreshing toward high-bandwidth topological photonic modulation [52–55]. This electrically tailored liquid-crystal topological photonic platform may open new opportunities for dynamic structured-light communication, reconfigurable optical information processing, and topology-enabled light-matter interaction [17, 22, 56–60].

4 | Materials and methods

4.1 | Optical Setup and Voltage Driving

A 633 nm He-Ne laser was used as the incident source. The beam passed through a linear polarizer (LP) and a quarter-wave plate (QWP) to prepare the input circular polarization before entering the patterned liquid-crystal spin-orbit device. The sample was mounted on a rotation stage and a three-axis translation stage to align the device angle and transverse position.

An alternating voltage was applied to the ITO electrodes with a signal generator. Unless otherwise stated, all voltages are reported as peak-to-peak voltages V_{pp} ; the voltage range was

0–10 V and the driving frequency was 10 kHz. The output beam was analyzed with a quarter-wave plate and a linear polarizer. The selected polarization channel was focused with a 300 mm plano-convex lens onto either a photodetector for dynamic measurements or a CMOS camera for polarization-resolved imaging. For Stokes reconstruction, six intensity images were recorded in the H/V, D/A, and R/L analysis bases. The detailed optical layout, polarization-projection settings and TTL-synchronized acquisition scheme are provided in Note S6 and Figure S6.

4.2 | Device Fabrication

Patterned liquid-crystal spin-orbit devices were fabricated using SD1-based photoalignment in ITO-glass cells. ITO-coated glass substrates were cleaned, coated with an SD1 photoalignment layer, and annealed. Two SD1-coated substrates were assembled into empty cells with spacers of prescribed thickness, followed by DMD-assisted polarized UV exposure to write the target in-plane director field $\alpha(x, y)$. Nematic liquid crystal E7 was then filled into the patterned empty cells by capillary action and cooled to room temperature [61]. The final cell thicknesses were measured by interferometry. Detailed fabrication and photoalignment procedures are provided in Note S7.

4.3 | Device Implementation and Cross-Device Validation

Three independent devices were used to test the control principle. Device 1 (thickness $\approx 3.78\mu\text{m}$) was used for first-order switching $N_{sk} \approx 1$. Measurements on this device are shown in Figures 2, 3, and 4a,b. Device 2 (thickness $\approx 3.85\mu\text{m}$) was fabricated for generating a second-order skyrmion texture, yielding a signed skyrmion number of $N_{sk} \approx -2$ under the adopted helicity and coordinate convention (Figure 4c,d). Device 3 (thickness $\approx 1.46\mu\text{m}$) was prepared with a lower initial retardance, optimized for voltage switching at 0 and 4 V, enabling binary vortex-skyrmion bit writing (Figure 5). These devices were not different realizations of the same sample, but provided cross-validation of the mechanism under different conditions.

4.4 | Retardance Calibration

The voltage-dependent retardance was calibrated from the relative energies measured in the co-polarized and cross-polarized circular channels. For every voltage, the background-subtracted intensities were integrated over the same fixed calibration region Ω_{cal} . The converted-channel fraction was defined as

$$F_{-\sigma_0}(V) = \frac{\int_{\Omega_{cal}} I_{-\sigma_0}(x, y; V) dA}{\int_{\Omega_{cal}} [I_{\sigma_0}(x, y; V) + I_{-\sigma_0}(x, y; V)] dA} \approx \sin^2 \left[\frac{\delta(V)}{2} \right] \quad (5)$$

The physical branch of $\delta(V)$ was selected from the continuity of the voltage scan, the estimated initial retardance of the device and the monotonic trend expected from the liquid-crystal response. The inferred $\delta \approx 2\pi$ and $\delta \approx \pi$ coordinates were then used as the experimental reference points for the topological window and collapse measurements. The liquid-crystal forward model used to rationalize this voltage-retardance relation is described in Note S1.

4.5 | Stokes Reconstruction and N_{sk} Calculation

All polarization-resolved images used for Stokes reconstruction were recorded at the same observation plane, corresponding to the propagated field profiles $u_{\text{G}}(r)$ and $u_{\text{L}}(r)e^{i\phi}$ used in Equation (2). The skyrmion number N_{sk} was obtained from the reconstructed Stokes field of the output.

We recorded six intensity images in the horizontal (H), vertical (V), diagonal (D, $+45^\circ$), antidiagonal (A, -45°), right-circular polarization (RCP), and left-circular polarization (LCP) bases. After background subtraction and image registration, the normalized Stokes parameters were calculated at each pixel as

$$s_1 = \frac{I_{\text{H}} - I_{\text{V}}}{I_{\text{H}} + I_{\text{V}}}, s_2 = \frac{I_{\text{D}} - I_{\text{A}}}{I_{\text{D}} + I_{\text{A}}}, s_3 = \frac{I_{\text{R}} - I_{\text{L}}}{I_{\text{R}} + I_{\text{L}}} \quad (6)$$

Here, I_{D} and I_{A} denote the intensities measured in the $+45^\circ$ and -45° linear-polarization bases, respectively, whereas I_{R} and I_{L} denote those measured in the RCP and LCP bases, respectively [10, 36, 37, 62]. The skyrmion density is calculated from the experimental Stokes parameters as

$$\rho_{\text{sk}}(x, y) = \frac{1}{4\pi} \mathbf{s} \cdot \left(\frac{\partial \mathbf{s}}{\partial x} \times \frac{\partial \mathbf{s}}{\partial y} \right) \quad (7)$$

The skyrmion number was then calculated by numerical integration:

$$N_{\text{sk}} = \iint_{\Omega} \rho_{\text{sk}}(x, y) dx dy \quad (8)$$

where $\mathbf{s} = (s_1, s_2, s_3)$. Because the region of interest of the skyrmion texture changes with V , we used an active-contour (snake) algorithm to define the integration boundary Ω [63]. An initial contour was placed around the texture and iteratively converged to the edge of the measured Stokes map [64]. The final contour defined the region of interest. All snake initialization, filtering, and convergence parameters were kept fixed across each voltage scan. Near the collapse region, where the texture becomes strongly contracted and the optical signal decreases, the complete recovery of the texture boundary and the uniformity of the boundary polarization cannot be fully verified; therefore, the extracted N_{sk} values in this regime should be interpreted as finite-ROI estimates.

4.6 | Dynamic Response and Bit Reconstruction

Before the dynamic measurements, the two bias levels used for bit writing were calibrated by full Stokes reconstruction and assigned to the vortex-like and skyrmion states. The dynamic response was recorded under left-circularly polarized (LCP) illumination by detecting the converted right-circularly polarized (RCP) component. The RCP component was selected using a quarter-wave plate and a linear polarizer, providing the polarization channel with the highest optical contrast between the two calibrated endpoint states. The photodetector signal was normalized as R_{norm} and used to characterize the optical transient between the two calibrated endpoint states.

The switching times were defined by the 10%–90% falling or rising intervals of R_{norm} . The corresponding 403 Hz value was estimated from the sum of the two response times and represents an upper cycling rate derived from the optical response. The voltage-dependent transient traces and repeated-cycle statistics used for response-time extraction are provided in Figure S5. For bit reconstruction, a 16×16 binary image was converted into a raster-scanned 256-bit voltage sequence, with logic 0 and logic 1 implemented by 0 and 4 V, respectively. At each bit position, six polarization-resolved images were acquired at the prescribed readout time and processed using the Stokes reconstruction procedure described above. The resulting N_{sk} values were then rearranged according to the original raster order to recover the encoded image. No additional fitted threshold or classifier was used in the main-text reconstruction.

Author Contributions

L.-L.M., Y.-Q.L., and Y.-J.S. conceived the idea. L.-L.M., Y.-Q.L., Z.-Y.G., and Y.-P.T. designed experiments. Y.-P.T. and Z.-Y.G. performed the experiments, analyzed and simulated the data with the assistance of Z.-Y.W., L.-Y., L.-Y.W., N.-M.C., Y.W., N.W. Y.-P.T. and Z.-Y.G. co-wrote the paper and validated by L.-L.M., Y.-J.S., N.-M.C., and Y.-Q.L. L.-L.M. and Y.-Q.L. supervised the project.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data underlying the results presented in this paper are available from the corresponding author upon reasonable request.

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Supporting Information

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

Supporting File 1: lpor72000-sup-0001-MovieS1.mp4.

Supporting File 2: lpor72000-sup-0002-MovieS2.mp4.

Supporting File 3: lpor72000-sup-0003-MovieS3.mp4.

Supporting File 4: lpor72000-sup-0004-SuppMat.docx.