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Magnet-free reconfigurable alterspin photonics at optical frequencies

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Abstract

Altermagnetism is a compensated magnetic order in which spin polarization alternates between symmetry-related momenta despite zero net magnetization¹⁻⁴. Recently, an altermagnetic photonic crystal was demonstrated by mapping electron spin onto light spin, while still relying on gyromagnetic materials and magnetic bias⁵. Hence, it is rather elusive to extend the altermagnetism concept to optical frequencies⁶. Here we realize reconfigurable magnet-free alterspin photonics in an all-dielectric photonic crystal across 740–800 nm. The in-plane square lattice fixes the four-

period angular form of the alterspin texture, while an extrinsic out-of-plane dielectric perturbation controls its sign and amplitude. A liquid droplet enables writing, erasing, and reversing the alterspin texture. We further establish a criterion to evaluate the alterspin order and quantify the measured texture. Our results provide a route toward visible-to-near-infrared alterspin photonic systems that are magnet-free and externally reconfigurable.

Main text

Alternating spin polarization across symmetry-related momentum sectors is a hallmark of altermagnetism¹⁻⁴, and circular polarization provides a direct optical spin analog⁷⁻⁹ for constructing alterspin textures. Existing photonic demonstrations^{5,10}, however, have focused on microwave gyromagnetic platforms¹¹⁻¹³, where staggered magnetic biases of opposite polarity generate an alterspin texture. This route becomes difficult at optical frequencies^{6,14}, where gyromagnetic response diminishes rapidly, and suitable nanoscale magnetic-bias sources are lacking¹⁵⁻¹⁷ (Supplementary Note 1). Theoretical proposals have therefore considered replacing opposite magnetic polarities with opposite material chiralities^{18,19}. Yet material chiral response is typically weak and does not provide the pronounced polarity contrast available from opposite magnetic biases. These limitations leave an optical-frequency route to alterspin textures unresolved.

Reconfiguring an alterspin texture poses a separate challenge. In gyromagnetic implementations, reversal requires switching the polarity of each magnetic bias; in chiral schemes, it requires reversing the material chirality, neither of which is readily achievable in operation. Dielectric photonic structures make chirality much easier to engineer geometrically than at the material level²⁰, but this does not remove the reconfiguration difficulty: once fabricated, the structural handedness is likewise fixed. Recent ferroelectric studies suggest a different control

principle: an out-of-plane polarization can control an in-plane texture²¹⁻²³. More generally, the degree of freedom used to reconfigure a texture need not be the one that organizes it. Can this reconfiguration strategy be realized at optical frequencies in a dielectric platform?

Here, we realize reconfigurable magnet-free alterspin photonics in an all-dielectric photonic crystal (Fig. 1A), where in-plane and out-of-plane symmetries play separate roles. The in-plane square lattice organizes the alterspin texture into a four-period angular form, whereas an out-of-plane dielectric perturbation controls its sign and amplitude. Theoretically, a Maxwell-Hamiltonian analysis²⁴⁻²⁷ identifies the symmetry constraints underlying this control. Experimentally, we develop a suspended photonic-crystal platform in which a single water droplet serves as the reversible dielectric perturbation: moving it between opposite sides reverses the alterspin texture, whereas removing it suppresses the texture. We further introduce a criterion to assess alterspin order across wavelengths, dielectric contrasts, and photonic implementations.

Magnet-free platform for alterspin photonics

We implement this platform using a suspended silicon-nitride (SiN_x) photonic-crystal slab patterned with a square lattice of rounded-square holes. As shown in the cross-sectional and top-view scanning electron micrographs in Fig. 1B, the fabricated slab maintains a uniform thickness and a well-defined periodic structure. The lattice constant a , hole side length b , and slab thickness h define the photonic-crystal geometry, with the corresponding unit cell shown schematically in Fig. 1C. Across 740–800 nm, SiN_x is an optically isotropic, nonmagnetic dielectric with $n \approx 2$. The suspended geometry provides access to both sides of the slab for dielectric control. Before any dielectric perturbation, both sides are surrounded by air, with $n_1 = n_2 = 1$. The air- SiN_x -air

configuration therefore defines the vertically symmetric reference, preserving the in-plane mirrors M_x , M_y , and M_d , and the out-of-plane mirror M_z .

To selectively break the out-of-plane symmetry, the SiN_x surface is treated with trichloro(1H,1H,2H,2H-perfluorooctyl)silane to suppress water penetration through the holes. The measured water contact angle of 117° in Fig. 1C confirms the hydrophobic surface, which favors a Cassie wetting state^{28,29} and helps maintain water on one side of the slab. This preparation enables a stable water- SiN_x -air configuration, with water above the slab and air below it, where $n_1 = 1.33$ and $n_2 = 1$. As illustrated in Fig. 1A, this configuration breaks M_z while leaving the square lattice and its in-plane mirrors unchanged. We then characterize the radiation in momentum space defined by the in-plane momentum components k_x and k_y . Fabrication and measurement details are provided in the Methods.

Fig. 1D shows the resulting alterspin texture in the normalized circular-polarization Stokes parameter S_3 , with momentum coordinates normalized by the free-space wavevector $k_0 = 2\pi/\lambda$. The sign of S_3 distinguishes the two circular-polarization states, with $S_3 > 0$ and $S_3 < 0$ corresponding to right- and left-handed circular polarization along the collection direction, respectively. To visualize the angular form more clearly, we trace S_3 along the selected isofrequency contour and plot it as $S_3(\varphi)$, where $\varphi = \arg(k_x + ik_y)$ is the azimuthal angle. Both calculations and measurements show a four-period angular form. These results show a magnet-free alterspin texture in an all-dielectric photonic platform when the out-of-plane mirror symmetry is broken, while the in-plane lattice remains unchanged.

Symmetry and Maxwell-Hamiltonian origin

The alterspin texture follows from the separate roles of the in-plane and out-of-plane symmetries, as summarized in Fig. 2A. In the vertically symmetric reference, $n_1 = n_2$, and the two sides of the slab are related by the out-of-plane mirror M_z . When $n_1 \neq n_2$, M_z is broken while the in-plane mirrors M_x , M_y , and M_d remain unchanged. To describe how these symmetries constrain the polarization response, we formulate the Bloch-Maxwell eigenproblem as a two-component Maxwell Hamiltonian in the (H_x, H_y) basis, following the effective-Hamiltonian framework^{26,27}: $\mathcal{H} = d_0 I + d_x \sigma_x + d_y \sigma_y + d_z \sigma_z$, where σ_i are the Pauli matrices. As derived in Supplementary Note 2, d_0 determines the eigenfrequency dispersion, while d_x and d_z describe the two linear Stokes components. The key term d_y sets the relative phase between H_x and H_y , and therefore controls the circular-polarization component $S_3 = -2 \text{Im}(H_x H_y^*) / (|H_x|^2 + |H_y|^2)$. This coupling arises from the Maxwell fields themselves rather than from a gyromagnetic material response.

The two symmetry roles then become explicit. For $n_1 = n_2$, the M_z -related contributions to d_y cancel, suppressing S_3 . When $n_1 \neq n_2$, this cancellation is removed while the in-plane symmetry constraints remain unchanged. The mirrors M_x , M_y , and M_d require $d_y(-k_x, k_y) = -d_y(k_x, k_y)$, $d_y(k_x, -k_y) = -d_y(k_x, k_y)$, and $d_y(k_y, k_x) = -d_y(k_x, k_y)$, respectively^{30,31}. The lowest-order term satisfying these constraints is $d_y \propto k_x k_y (k_x^2 - k_y^2)$. With $k_x = k \cos \varphi$ and $k_y = k \sin \varphi$, this gives

$$S_3 \propto k_x k_y (k_x^2 - k_y^2) \propto \sin 4\varphi \quad (1)$$

Thus, the in-plane square lattice fixes the four-period angular form of the alterspin texture, whereas the out-of-plane dielectric perturbation controls its sign and amplitude. The four-period form

corresponds to eight alternating-sign sectors in momentum space, labeled A_i and B_i in Fig. 2A, with opposite signs within each quadrant.

We next identify the optical mode underlying the alterspin response. Fig. 2B shows the calculated dispersion along $X \leftarrow \Gamma \rightarrow M$, spanning the 0° ($X \leftarrow \Gamma$) and 45° ($\Gamma \rightarrow M$) high-symmetry directions of the square lattice. The color scale denotes the transverse-magnetic fraction η_{TM} , defined by the relative contribution of E_z to the total electric-field energy. The fundamental transverse-magnetic-like mode TM_1 lies within the studied wavelength range and carries a strong normal electric-field component E_z , as shown by the in-plane and cross-sectional field maps in Fig. 2C. Because E_z samples the dielectric media above and below the slab and couples H_x and H_y through Maxwell's curl equation, the out-of-plane dielectric perturbation changes their relative phase and hence S_3 . Fig. 2D visualizes this phase coupling at a representative momentum in the A_1 sector. The two magnetic-field combinations shown are constructed from the same H_x and H_y components that define S_3 and represent the local right- and left-handed circular-polarization responses in this sector.

Reconfigurable control and texture reversal

The theoretical analysis above motivates experimental mapping of the alterspin texture along the TM_1 dispersion. Fig. 3A summarizes the measurement procedure. Momentum-resolved spectra first identify the TM_1 band in simulation and experiment. At each selected wavelength, we measure the two circular-polarization channels separately: their sum gives the momentum-space intensity map, while their normalized difference gives the corresponding S_3 map on the TM_1 isofrequency contour. Repeating this procedure across the measured wavelength range yields the alterspin texture along the TM_1 dispersion.

Fig. 3B shows the water-SiN_x-air configuration, with water above the slab and air below it. The central panel stacks the measured S_3 contours across 740–800 nm in 10-nm steps in the three-dimensional space defined by the two in-plane momentum coordinates and the wavelength, while the lower-left panel shows the top-view projection of the same data. The right panel unfolds each contour into the angular profile $S_3(\varphi)$ for a clearer view of the angular form. As the wavelength increases, the isofrequency contour evolves along the TM₁ dispersion and the S_3 amplitude becomes more pronounced. The sign distribution, however, remains largely unchanged, showing that the measured texture retains the same four-period angular form across the measured wavelength range.

We then reverse the out-of-plane dielectric perturbation on the same suspended photonic-crystal slab by moving the water droplet to the opposite side. In the air-SiN_x-water configuration shown in Fig. 3C, the S_3 distribution reverses sign across the measured wavelength range, while the TM₁ dispersion and four-period angular form are preserved. This reversal is observed consistently in both the momentum-space maps and angular profiles. This indicates that the sign distribution of the alterspin texture is controlled by the out-of-plane dielectric configuration rather than by fabrication asymmetry, droplet-induced optical artifacts, or accidental in-plane chirality. Unlike schemes based on built-in structural asymmetry or chirality³²⁻³⁶, here the in-plane lattice symmetry remains unchanged while the out-of-plane dielectric perturbation reversibly controls the alterspin texture.

After removing the water droplet, we measure the same slab again in the air-SiN_x-air reference configuration, as detailed in Supplementary Note 3. The S_3 amplitude is strongly reduced and the four-period alterspin texture is suppressed. Because changing the surrounding refractive index also shifts the TM₁ dispersion, we further fabricate a thickness-compensated slab

using an empirical relation to restore the TM_1 band to the 740–800 nm wavelength range. This compensated reference likewise shows no appreciable four-period alterspin texture. Together, these measurements demonstrate reversible control of the alterspin texture by adding or removing the droplet and moving it between the two sides of the suspended slab.

Quantitative assessment of alterspin order

For each fixed configuration, the measured texture retains the four-period $S_3 \propto \sin 4\varphi$ angular form across wavelengths. Its amplitude changes along the band dispersion, while its sign distribution remains largely unchanged. To quantitatively assess the alterspin order, we define an alterspin-texture asymptotic coefficient

$$C_{\text{alt}}(\lambda) = \frac{\int_w S_3(\mathbf{k}, \lambda) \sin[4\varphi(\mathbf{k})] d^2k}{\int_w \sin^2[4\varphi(\mathbf{k})] d^2k} \quad (2)$$

Here, w selects the isofrequency contour used to assess how closely the measured S_3 distribution follows the four-period angular form. The sign of C_{alt} distinguishes the two opposite alterspin textures, while its magnitude measures the strength of the four-period alterspin order. For an ideal texture, $S_3 = \sin 4\varphi$ and $C_{\text{alt}} = 1$. For a texture with vanishing S_3 amplitude or strong deviation from the $\sin 4\varphi$ form, $C_{\text{alt}} = 0$.

Fig. 4A applies this criterion to the two water configurations introduced in Fig. 3, together with the thickness-compensated air-SiN_x-air reference. Filled diamonds denote measurements, and crosses connected by dashed lines denote calculations. The two water configurations give opposite signs of C_{alt} , indicating reversed sign distributions. As wavelength increases, the calculated magnitudes stabilize above 0.5, while the measured magnitudes approach 0.4. The measured magnitudes are lower but follow the same spectral trend. The vertically symmetric air-SiN_x-air reference remains near zero, consistent with the absence of a four-period alterspin texture.

We next compare the discrete configurations using the dielectric contrast $n_1 - n_2$, where n_1 and n_2 are the refractive indices above and below the photonic-crystal slab. We fix one side as air and place the higher-index medium on the other side. For each prescribed contrast, $n_1 = 1 + \max(n_1 - n_2, 0)$ and $n_2 = 1 + \max(n_2 - n_1, 0)$. A positive contrast places the higher-index medium above the slab, a negative contrast places it below, and zero contrast gives the vertically symmetric reference.

The calculated map in Fig. 4B shows how the angular profile $S_3(\varphi)$ changes with the dielectric contrast $n_1 - n_2$. The four-period angular form is preserved across the full range. Increasing the contrast magnitude strengthens the S_3 amplitude, whereas reversing the contrast reverses its sign. Applying the same criterion gives the black dashed switching curve in Fig. 4C. Crosses mark calculations for the experimentally realized configurations, using the corresponding sample geometries, and filled diamonds show the corresponding measured C_{alt} values for five air-, water-, and glass-based configurations. The two glass cases, detailed in Supplementary Note 4, extend the accessible dielectric contrast. Although their measured magnitudes are lower than calculated, all five points follow the same switching trend. Fig. 4D shows the corresponding angular profiles. Dashed curves denote calculations, open circles denote measurements, and the colors follow Fig. 4C. The profiles evolve from one four-period form, through the symmetric reference, to its sign-reversed counterpart.

The same criterion also allows comparison across different photonic implementations. As one example, a recent study²⁰ used staggered planar-chiral structures in place of magnetic bias to generate alternating sign patterns, including a four-period pattern similar to that studied here. We digitized the reported well-separated fundamental-band textures and applied the same criterion, obtaining C_{alt} magnitudes of approximately 0.21 in simulation and 0.12 in experiment. These

lower values are consistent with the weaker circular-polarization response, while reconfiguration is less straightforward for the fixed planar-chiral geometry. More generally, the criterion can in principle be extended to alterspin textures of different orders by replacing $\sin 4\varphi$ with the corresponding angular form.

Discussion

We have realized magnet-free and reconfigurable alterspin photonics at optical frequencies using an all-dielectric photonic crystal. Across 740–800 nm, the system supports an alterspin texture with a clear four-period angular form and substantial circular-polarization amplitude. In-plane symmetry organizes this four-period angular form, which provides a physical basis for quantifying and comparing alterspin order across different implementations. The out-of-plane dielectric configuration controls the sign and amplitude of the texture, providing a handle for reconfiguration: a single water droplet writes, erases, and reverses the alterspin texture. This approach avoids reliance on magnetic responses that are largely absent at optical frequencies. Under the same quantitative criterion, our measured texture exhibits a larger alterspin-order magnitude than the recent planar-chiral implementation while retaining reversible control. Together, these results provide a route to reconfigurable alterspin photonics at optical frequencies.

219 Figures & figure captions

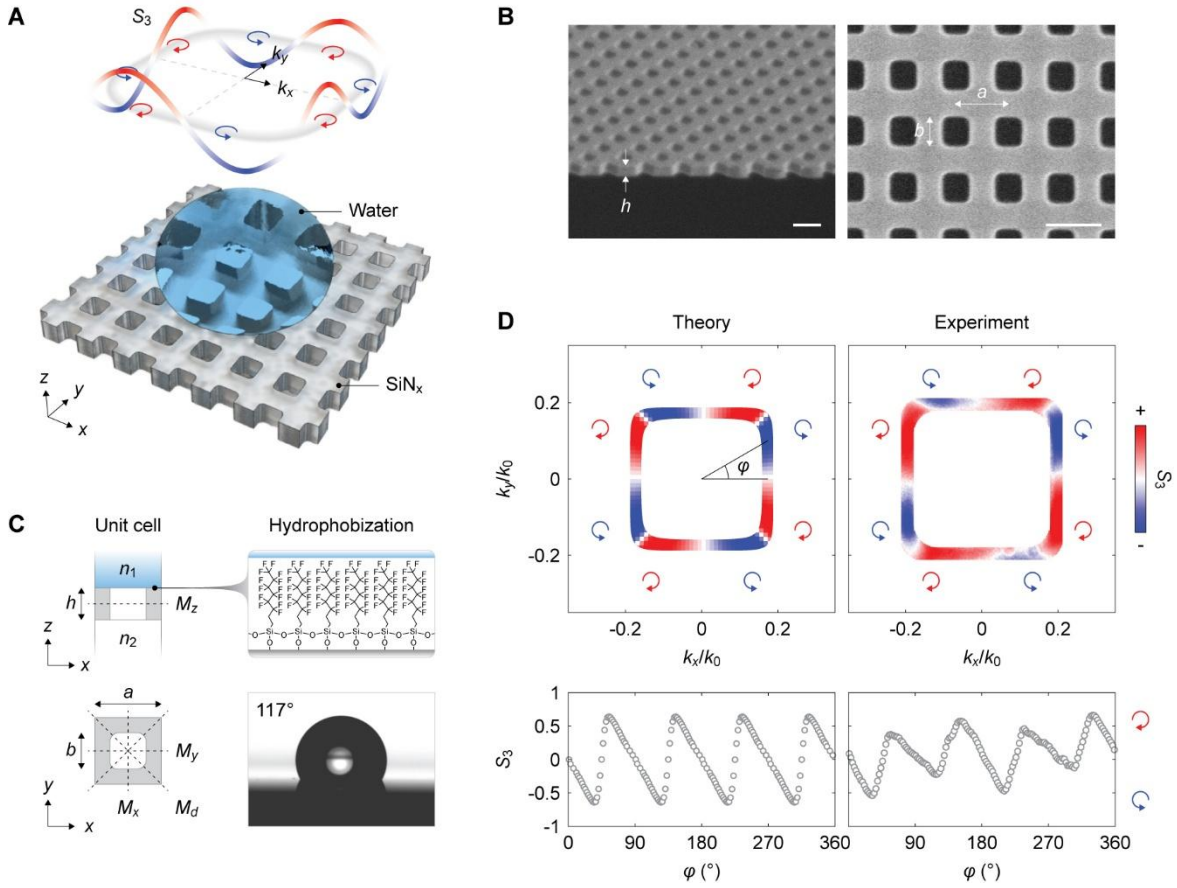


Fig. 1 | Magnet-free alterspin texture in an all-dielectric photonic crystal. **A**, Conceptual schematic. A water droplet provides an out-of-plane dielectric perturbation to a suspended SiN_x photonic-crystal slab while leaving the in-plane square lattice unchanged. **B**, Cross-sectional and top-view scanning electron micrographs of the fabricated suspended slab. The lattice constant a , hole side length b , and slab thickness h define the geometry. Scale bars, 500 nm. **C**, Unit-cell symmetry and surface preparation. n_1 and n_2 denote the upper and lower refractive indices. M_z is the out-of-plane mirror, and M_x , M_y , and M_d are the in-plane mirrors. Fluorinated-silane hydrophobization gives a water contact angle of 117° , favoring a Cassie state that suppresses water penetration through the holes. **D**, Calculated and measured normalized circular-polarization Stokes parameter S_3 for the water-SiN_x-air configuration, obtained using a 10-nm spectral window

centered at $\lambda = 780$ nm. Here, k_x/k_0 and k_y/k_0 are the normalized in-plane momenta, $k_0 = 2\pi/\lambda$, and φ is the azimuthal angle. The upper maps show the alterspin texture, and the lower panels show its four-period angular form along the selected isofrequency contour.

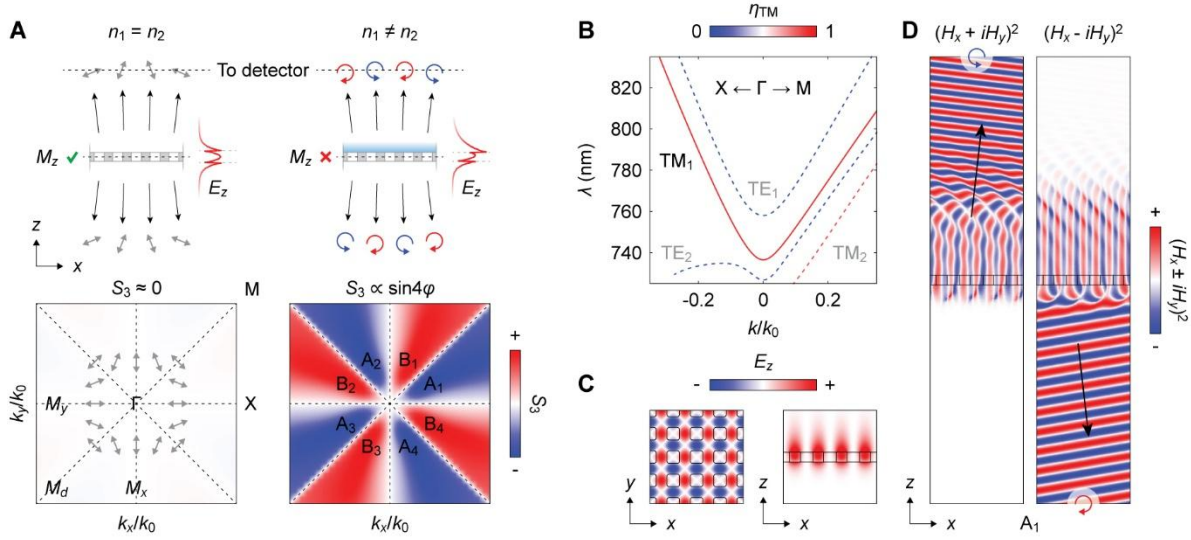


Fig. 2 | Symmetry and Maxwell origin of the alterspin texture. **A**, Separate roles of the out-of-plane and in-plane symmetries. In the vertically symmetric reference configuration, $n_1 = n_2$ and the out-of-plane mirror M_z suppresses the circular-polarization component S_3 . When $n_1 \neq n_2$, M_z is broken while the in-plane mirrors remain unchanged. The preserved in-plane symmetries enforce $S_3 \propto \sin 4\varphi$, giving the four-period angular form. The alternating sectors are labeled A_i and B_i , with subscripts denoting the four quadrants. **B**, Calculated band dispersion along $X \leftarrow \Gamma \rightarrow M$, colored by the transverse-magnetic fraction η_{TM} . TM_1 is the fundamental transverse-magnetic-like band, and dashed curves mark nearby TE_1 , TE_2 , and TM_2 bands. k/k_0 is the normalized signed momentum along the displayed path, with negative and positive values corresponding to $X \leftarrow \Gamma$ and $\Gamma \rightarrow M$, respectively. λ denotes the free-space wavelength. **C**, In-plane and cross-sectional maps of the normal electric-field component E_z for TM_1 , showing the field component that

samples the dielectric media above and below the slab. **D**, Two magnetic-field combinations constructed from H_x and H_y at a representative momentum in the A_1 sector, showing the local right- and left-handed circular-polarization responses associated with S_3 .

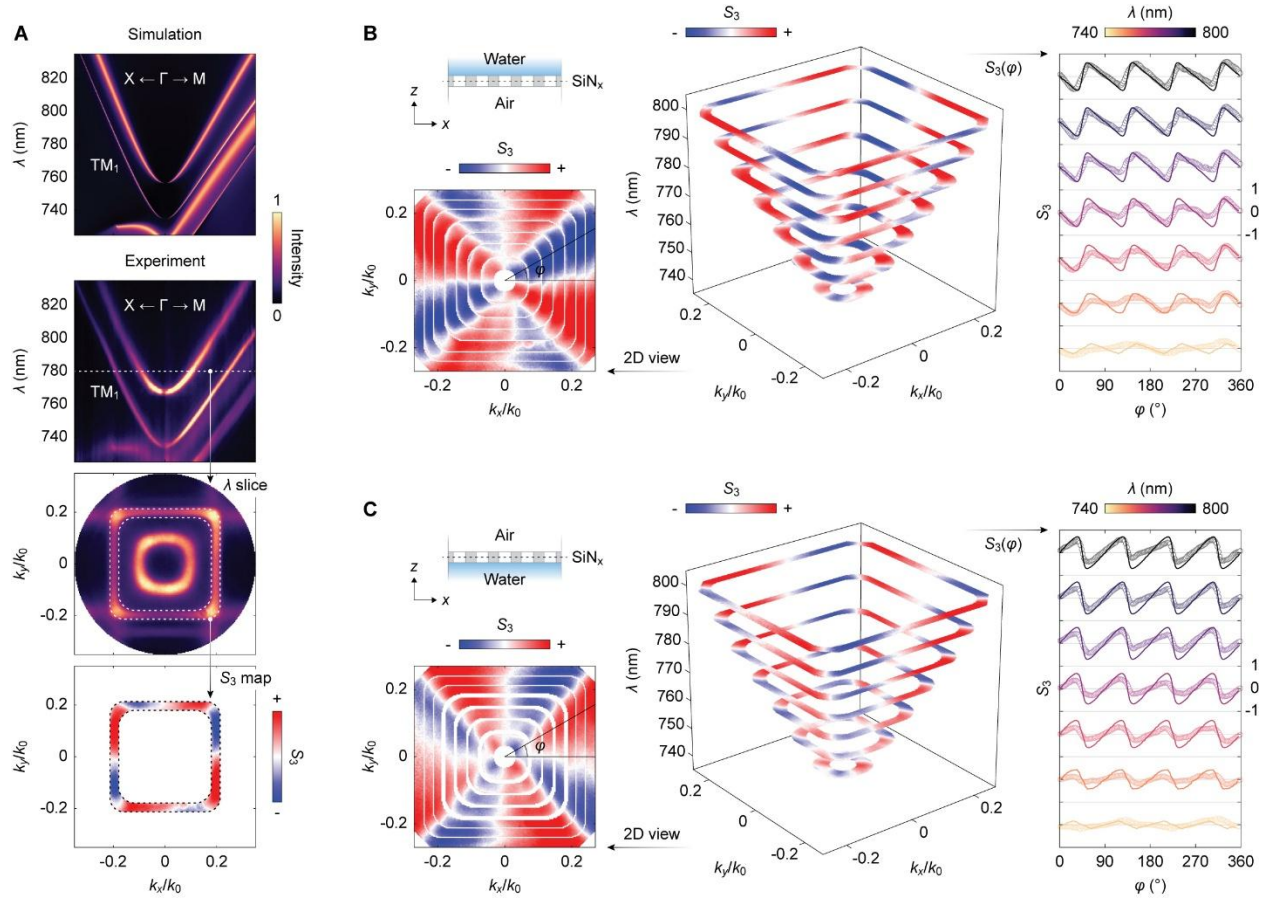


Fig. 3 | Experimental mapping and reversal of the alterspin texture. **A**, Measurement procedure. From top to bottom, the panels show the simulated and measured momentum-resolved spectra, the momentum-space intensity map, and the corresponding S_3 map on the TM_1 isofrequency contour. The spectra are taken along $X \leftarrow \Gamma \rightarrow M$ to identify TM_1 . The white dashed line marks the center wavelength for momentum-space imaging, with a 10-nm spectral window used for the lower maps. Dashed rounded-square contours mark the TM_1 isofrequency contour. The intensity and S_3 maps are obtained from the sum and normalized difference of the two

circular-polarization channels, respectively. **B**, Water-SiN_x-air configuration. The upper-left panel shows the vertical dielectric configuration. The central panel stacks measured S_3 contours across 740–800 nm in 10-nm steps in the three-dimensional space defined by the two normalized in-plane momentum coordinates and the wavelength. The lower-left panel shows the top-view projection of the same data, and the right panel unfolds the contours into angular profiles $S_3(\varphi)$. Solid curves and open circles denote calculations and measurements, respectively, with profiles vertically offset for clarity. **C**, Air-SiN_x-water configuration measured on the same suspended photonic-crystal slab. Moving the droplet to the opposite side reverses the S_3 sign while preserving the TM₁ dispersion and four-period angular form.

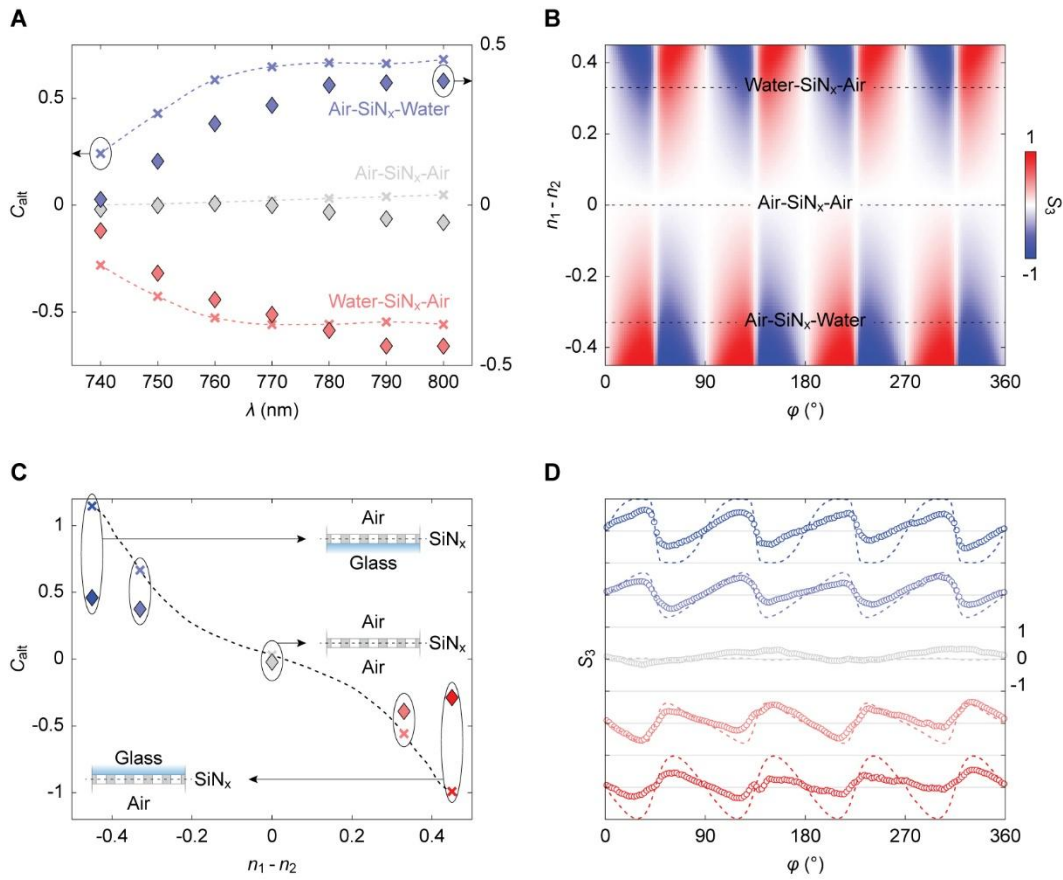


Fig. 4 | Alterspin order under varying dielectric contrast. **A**, Alterspin-texture asymptotic coefficient C_{alt} as a function of wavelength λ for air-SiN_x-water (light blue), air-SiN_x-air (gray), and water-SiN_x-air (light red). Filled diamonds denote measurements, read from the right axis, and crosses connected by dashed lines denote calculations, read from the left axis. **B**, Calculated $S_3(\varphi)$ at $\lambda = 780$ nm as a function of azimuthal angle φ and dielectric contrast $n_1 - n_2$, where n_1 and n_2 are the upper and lower refractive indices. One side is fixed as air, such that the higher-index medium lies above or below the slab according to the sign of $n_1 - n_2$. Dashed horizontal lines mark representative water-SiN_x-air, air-SiN_x-air, and air-SiN_x-water configurations. **C**, C_{alt} at $\lambda = 780$ nm as a function of $n_1 - n_2$. The black dashed curve shows the calculated switching trend; crosses and filled diamonds mark calculated and measured values, respectively, for the experimental configurations. Dark blue, light blue, gray, light red, and dark red denote air-SiN_x-glass, air-SiN_x-water, air-SiN_x-air, water-SiN_x-air, and glass-SiN_x-air, respectively. **D**, Corresponding angular profiles for the five configurations in **C**. Dashed curves show calculations, open circles show measurements, and colors follow **C**.

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Methods

Sample fabrication. Commercial double-side-polished, (100)-oriented silicon wafers (μm thick, TopVendor), coated on both sides with 300-nm-thick low-pressure chemical vapor deposition (LPCVD) SiN_x , were diced into $1.5\text{ cm} \times 1.5\text{ cm}$ chips. After cleaning, ZEP520A (ZEON) was spin-coated at 1500 rpm for 70 s and baked at $210\text{ }^\circ\text{C}$ for 5 min, followed by ESpacer (300Z, Showa Denko) at 1000 rpm for 70 s. Photonic crystal arrays ($a = 480\text{ nm}$, $b = 260\text{ nm}$, 200×200 periods) were patterned by electron-beam lithography (JBX-6300FS, JEOL) at 400 pA and $280\text{ }\mu\text{C cm}^{-2}$, typically six arrays per chip with 200- μm spacing. After exposure, ESpacer was removed in deionized water, and the sample was developed in amyl acetate for 2 min and isopropanol for 30 s. The pattern was transferred into the front-side SiN_x by inductively coupled plasma (ICP) etching (PlasmaPro 100 Cobra, Oxford Instruments) using CHF_3/SF_6 flow rates of 60/15 sccm at $20\text{ }^\circ\text{C}$, 650 W ICP power, 30 W RF power, and 8 mTorr. Nine 22-s cycles produced an etch depth of about 270 nm. Residual ZEP was treated with UV/ozone (PSD Pro, Novascan) at $60\text{ }^\circ\text{C}$ for 5 min to facilitate removal, then removed in dimethyl sulfoxide (DMSO) for more than 1 h, followed by 10 min of sonication.

Backside alignment markers and release windows were then fabricated. For the markers, LOR 3A and S1805 were sequentially spin-coated at 4000 rpm for 70 s, then baked at $175\text{ }^\circ\text{C}$ for 5 min and at $125\text{ }^\circ\text{C}$ for 1 min, respectively. The markers were exposed by laser writing (LW405B, Microtech) at $223\text{ }\mu\text{J cm}^{-2}$, developed in MF319 for 1 min, rinsed in deionized water for 30 s, and aligned to the front-side arrays using the infrared mode of a mask aligner (MJB4, SÜSS Microtech). A 25-nm Al layer was deposited by thermal evaporation (Nano 36, Kurt J. Lesker) and lifted off in PG remover at $65\text{ }^\circ\text{C}$ for 1 h. A $1\text{ mm} \times 2\text{ mm}$ backside release window was patterned in AZ1512 by spin coating at 5000 rpm for 70 s, baking at $110\text{ }^\circ\text{C}$ for 1 min, and laser

writing at $445 \mu\text{J cm}^{-2}$, with the window aligned to the center of the front-side arrays. The pattern was developed in AZ400K/deionized water (1:4) for 30 s and rinsed in deionized water for 30 s. The exposed backside SiN_x was etched through with the same ICP recipe for 4 min, after which the remaining AZ1512 was removed in PG remover at 65°C for 1 h.

The exposed silicon was etched in 30 wt% potassium hydroxide (KOH) at 100°C with stirring at 800 rpm for approximately 9 to 10 h to form suspended SiN_x membranes, which were then transferred to ethanol and dried using a critical point dryer (CPD300, Leica). The suspended membranes used for the main experiments were thinned from the backside to a target SiN_x thickness of $h = 232 \text{ nm}$ using the same ICP recipe, with more than 30 nm removed to ensure that the photonic crystal holes were fully open. Both sides were cleaned by UV/ozone at 60°C for 10 min. The samples were exposed to trichloro(1H,1H,2H,2H-perfluorooctyl)silane vapor in a desiccator at 0.09 MPa for 1 h, gently blown with nitrogen for 30 s, and baked at 100°C for 30 min to form a hydrophobic surface. LOR 3A, S1805, MF319, and PG remover were from KayakuAM; AZ resists, AZ developers, solvents, and other chemicals were from Merck.

Numerical simulations. The mode profiles and momentum-space polarization textures were calculated with a frequency-domain finite-element model implemented in the Wave Optics Module of COMSOL Multiphysics 6.4. The simulated unit cell was treated as an open photonic-crystal slab, with Bloch periodic boundary conditions imposed in the x and y directions for in-plane momentum sweeping. Along the z direction, 300-nm-thick perfectly matched layers were used to absorb outgoing radiation. All materials were modeled as isotropic, nonmagnetic dielectrics, with dispersion and absorption neglected. The refractive indices of SiN_x , air, water, and glass were set to 2.0, 1.0, 1.33, and 1.45, respectively. The finite-element mesh was generated using the built-in physics-controlled meshing scheme. Calculations were run on a GPU-equipped

workstation with an NVIDIA RTX 4090. The momentum-resolved spectra were obtained using the rigorous coupled-wave analysis (RCWA) solver in Ansys Lumerical FDTD 2024 R2.

Optical measurements. Optical spectroscopy and momentum-space imaging were performed on an inverted microscope (Eclipse Ti, Nikon) equipped with an objective lens (CF Plan 20×/0.35 Epi SLWD, Nikon). The hydrophobized suspended SiN_x sample carrying a water droplet was placed on the microscope stage. When needed, a hydrophobized transparent glass piece was placed approximately 500 μm from the SiN_x surface to flatten and stabilize the droplet, suppress evaporation, and improve focusing stability, with no noticeable change to the momentum-space patterns. Blowing off the droplet with a rubber bulb blower restored the sample to its dry state. The sample was illuminated by the broadband amplified spontaneous emission tail of a diode laser (LuxX 638-150, Omicron-Laserage), and the same objective collected the reflected signal. Reflection from an unpatterned region was recorded as the background and subtracted from the measured data. The collected signal was directed to either an EMCCD camera (iXon Ultra 897, Andor) for momentum-space imaging or a spectrometer equipped with a CCD camera (Shamrock 303i and Newton 920, Andor) for momentum-resolved spectroscopy. Left- and right-handed circular-polarization channels were selected using circular polarizers (CP1L780/CP1R780, Thorlabs). Spectral windows were selected using band-pass filters (FBH series, Thorlabs) with 10-nm bandwidths and center wavelengths across 740–800 nm in 10-nm steps. The EMCCD was operated in normal mode without electron-multiplying gain, and a 200-μm entrance slit was used for momentum-resolved spectroscopy. The integration time was 1 min for both imaging and spectroscopy.

Data availability

All data are available in the Article and the Supplementary Information, and are also available from the corresponding author upon reasonable request.

Code availability

The source code for the calculations conducted in this study is available from the corresponding author upon reasonable request.

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Author contributions

Z.W., S.Y., and C.-W.Q. conceived the project. Z.W. fabricated the samples and carried out the optical measurements. Z.W. and S.Y. developed the theoretical framework and performed the numerical simulations. J.C. and M.L. provided input on the theory and simulations. K.L. performed the contact-angle measurements. M.C., Y.W., L.Z. and X.M. provided materials and fabrication support. Z.W. and S.Y. wrote the manuscript, with contributions from all authors. C.-W.Q. supervised the project and provided resources. All authors discussed the results and commented on the manuscript.

450 **Competing interests**

451 The authors declare no competing interests.

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