

Liquid photonic crystals enabling dual-variable magnetic modulation and mechanically stabilized display

Chunchao Xu¹, Yonghao Wang¹, Chengcheng Liu¹, Menglei Wang^{2,3}, Youhao Sun¹, Fulin Jia³, Fenglian Qi¹ (✉), Caifeng Ding¹ (✉)

¹ Key Laboratory of Optic-electric Sensing and Analytical Chemistry for Life Science, Shandong Key Laboratory of Analytical Chemistry for Life Science and Intelligent Detection, College of Chemistry and Molecular Engineering, Qingdao University of Science and Technology, Qingdao 266042, China

² Green Catalysis Center, and College of Chemistry, Zhengzhou University, Zhengzhou 450001, China

³ CAS Key Laboratory of Nanosystem and Hierarchical Fabrication, CAS Center for Excellence in Nanoscience, National Center for Nanoscience and Technology, Beijing 100190, China

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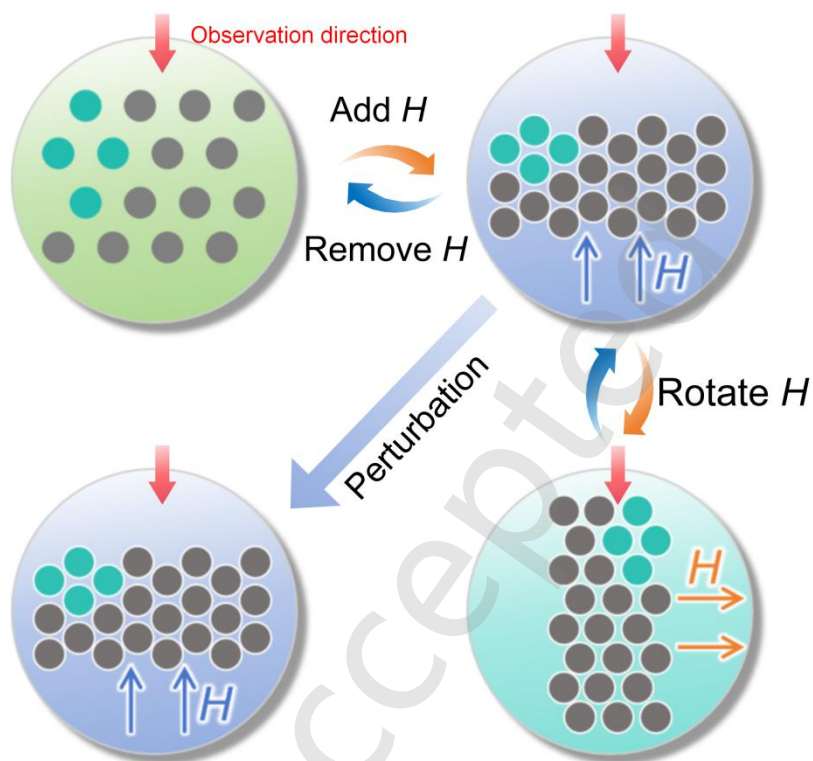
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We investigated the magnetic field application, field switching, and mechanical stability of the LPCs.



Research Article

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Chunchao Xu,¹ Yonghao Wang,¹ Chengcheng Liu,¹ Menglei Wang,^{2,3} Youhao Sun,¹ Fulin Jia,³

Fenglian Qi^{1,*} and Caifeng Ding^{1,*}

¹ Key Laboratory of Optic-electric Sensing and Analytical Chemistry for Life Science, Shandong Key Laboratory of Analytical Chemistry for Life Science and Intelligent Detection, College of Chemistry and Molecular Engineering, Qingdao University of Science and Technology, Qingdao 266042, China

² Green Catalysis Center, and College of Chemistry, Zhengzhou University, Zhengzhou 450001, China

³ CAS Key Laboratory of Nanosystem and Hierarchical Fabrication, CAS Center for Excellence in Nanoscience, National Center for Nanoscience and Technology, Beijing 100190, China

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✉ Address correspondence to Fenglian Qi, qifenglian@qust.edu.cn; Caifeng Ding, dingcaifeng@qust.edu.cn

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ABSTRACT:

Despite the operational advantages of liquid photonic crystals (LPCs) over solid counterparts for dynamically tunable structural color, their fragility and lack of structural stability remain critical bottlenecks. In this work, we overcome these limitations using magnetic nanoparticle-assembled LPCs that combine enhanced mechanical stability with full-visible-spectrum three-dimensional structural coloration achieved via precise control over particle size and concentration. Moreover, we introduce a dual-variable magnetic modulation strategy that operates through two modalities. Field strength (0-272 Gs) and field orientation (0°-90°) each enable modulation of both peak wavelength and intensity. Scanning electron microscopy reveals distinct particle arrangements under 0° and 90° field orientations, confirming that the orientation-dependent optical response originates from reconfigurable microscopic structures. This suggests that magnetic field orientation modulation can be achieved in three-dimensional PCs assembled from isotropic magnetic nanoparticles, offering a dual-variable magnetic modulation from strategies that rely on anisotropic particle design. Notably, the magnetically induced PCs exhibit substantially enhanced resistance to mechanical disturbances compared to their non-induced counterparts. Leveraging these capabilities, we demonstrate mechanically stabilized display using capillary-confined LPCs. These LPCs exhibit reversible color switching under magnetic actuation, which

maintains optical signal integrity under the mechanical shear force. By integrating full-visible-range coloration, dual-variable magnetic modulation, and enhanced mechanical stability, this work establishes a versatile platform for adaptive displays, anti-counterfeiting, and robust optical sensing.

KEYWORDS: photonic crystal; dual-variable; magnetic control; mechanically stabilized; display

1 Introduction

Photonic crystals (PCs) employ periodic dielectric structures to manipulate light, providing a versatile platform for structural color generation in displays¹, anti-counterfeiting², and optical sensing³. Colloidal self-assembly offers a particularly accessible route to fabricate PCs, where monodisperse nanoparticles organize into ordered lattices with photonic bandgaps^{4, 5}. Among various PC architectures, liquid photonic crystals (LPCs), in which ordered nanostructures are dispersed in a liquid medium, stand out by uniquely combining fluidity with reconfigurability⁶. Unlike PC arrays whose structures are permanently fixed along with the solvent evaporation, LPCs allow dynamic rearrangement of their constituent building blocks, thereby enabling responsive optical properties with active modulation. Additionally, substantial efforts have been devoted to advancing LPCs through external-field modulation, including electric^{7, 8}, thermal⁹, and chemical stimuli¹⁰, each enabling reversible tuning of structural color. The colloidal EPC is intrinsically a special electrically responsive liquid photonic crystal (LPC)¹¹. It operates at low voltages and enables continuous color tuning across the visible spectrum. Yang et. al. and co-workers have achieved 3D structural colors using strategies such as photonic crystal shrinking¹², three-dimensional printing of inverse opals¹³, and high-order photonic cavity modes¹⁴. Despite these advances, the pursuit of fast, remote, and precisely controllable actuation remains an active frontier.

Magnetic field actuation has attracted considerable interest for controlling LPCs owing to its non-contact operation, strong penetration capability, and rapid response kinetics^{15, 16}. A pioneered strategy was firstly demonstrated by Yin et al., who assembled superparamagnetic Fe₃O₄ colloidal nanoclusters (CNCs) into photonic structures under external magnetic fields, establishing a versatile platform for

fabrication of one-dimensional PC chains at low amounts of building blocks¹⁷. Subsequently, Fe₃O₄@SiO₂ core-shell nanostructures¹⁸⁻²⁰, nonuniform Fe₃O₄ CNCs²¹, and nonmagnetic colloidal particles²² were developed to construct magnetically responsive PCs with diverse optical performances. Despite these advances, most studies focused predominantly on modulating magnetic field strength as the control parameter, leaving the field orientation largely unexplored^{23, 24}. However, some demonstrations that achieve orientation-dependent optical responses typically rely on anisotropic building blocks, such as magnetic nanorods²⁵, nanocubes²⁶, or nanoplatelets²⁷, which lead to substantial synthetic complexity and limit material generality. Furthermore, the mechanical stability of LPCs under external disturbances remains largely unexplored under realistic conditions, and the transition from fundamental structural control to functional device prototypes, including displays and anti-counterfeiting labels, is still in its early stages. Finally, to compare and clarify these innovations with other groups' work, we have added a comparative Table S1 in the Supporting Information. Based on Yin group's work, we further developed a three-dimensional LPC by another saturated evaporation-induced method, which could directly construct the LPCs with tunable colors that almost covered the visible range by the adjustment of building block sizes. Notably, we found that both the magnetic field strength and orientation could achieve the optical modulation of LPCs. The diverse field control under LPCs gives more opportunity for the design of display with diverse patterns. Besides, as compared with the three-dimensional LPCs assembled by non-magnetic nanoparticles, such as silica spheres, the mechanically stabilized display under magnetic field could be regarded as another innovation of our work.

Here, we report a magnetic-field-induced self-assembly strategy that integrates the high-quality static LPC fabrication enabled by supersaturation evaporation²⁸ with dynamic dual-variable magnetic modulation using isotropic magnetic nanoparticles. By systematically tailoring particle size and concentration, we first achieve three-dimensional LPCs with strong structural colors covering the entire visible spectrum. We then introduce magnetic field strength and orientation as two control

parameters, demonstrating that both modalities modulate peak wavelength and intensity. Notably, the direction of intensity modulation depends on particle size and concentration, revealing a richer design space. Scanning electron microscopy reveals distinct microstructural rearrangements under varying magnetic field orientations, providing direct evidence for the observed orientation-dependent optical response. Moreover, the magnetically induced LPCs exhibit substantially enhanced mechanical stability compared to their non-field-induced state counterparts. Leveraging this property, we demonstrate mechanically robust patterned displays that maintain optical signal integrity under external compression. Collectively, this work establishes a versatile platform that bridges static LPC fabrication and dynamic dual-variable magnetic modulation, opening new avenues for adaptive displays, anti-counterfeiting, and mechanically robust optical sensing systems.

2 Experimental section

2.1 Materials. Iron chloride (FeCl_3) was supplied by Shanghai Aladdin Biochemical Technology Co., Ltd. L-Ascorbic acid (AA) and sodium hydroxide (NaOH) were purchased from Sinopharm Chemical Reagent Co., Ltd. Ethylene glycol (EG), ammonium hydroxide ($\text{NH}_3 \cdot \text{H}_2\text{O}$), and tetraethyl orthosilicate (TEOS) were procured from Shanghai Hushi Laboratorial Equipment Co., Ltd. Sodium acetate (NaAc) and poly(4-styrenesulfonic acid-co-maleic acid) sodium salt (PSSMA) were obtained from Sigma-Aldrich. All materials were used as received without further purification.

2.2 Synthesis of Monodisperse Fe_3O_4 Nanoparticles. Fe_3O_4 nanoparticles (143 nm diameter) were synthesized by hydrothermal method²⁹. Briefly, 0.65 g FeCl_3 , 40 mL EG, 3.0 g sodium acetate, 1.05 g poly(4-styrenesulfonic acid-co-maleic acid) sodium salt, 14 mg L-ascorbic acid, and 150 μL deionized water were sequentially added to a glass beaker. The mixture was vigorously stirred for 40 min until homogeneous, followed by the addition of 0.6 g NaOH. Stirring continued for 2 h until the NaOH was completely dissolved. The resulting mixture was transferred to a 50 mL flask and heated at 190 °C for 9 h in a preheated oven. The black precipitate was collected by centrifugation, washed three times with 30 mL of 50% (v/v) ethanol in water, then

washed three additional times with deionized water, and finally redispersed in 25 mL of water for storage. To obtain Fe₃O₄ nanoparticles of 197 nm diameter, the same procedure was followed except that the deionized water volume was adjusted to 80 μ L.

2.3 Silica Coating of Fe₃O₄ nanoparticles. Silica coating was performed via a modified Stöber process²⁹. Briefly, 25 mL of Fe₃O₄ nanoparticles solution was mixed with ethanol (160 mL) and NH₃·H₂O (8 mL) under sonication for 5 min. The mixture was transferred to a 250 mL three-neck flask equipped with mechanical stirring (400 rpm) and maintained at 38 °C in a water bath. Then, TEOS (0.8 mL in total) was then added in two equal portions (0.4 mL each), with a 20 min interval between additions. The resulting Fe₃O₄@SiO₂ magnetic nanoparticles were collected by centrifugation at 10000 rpm, washed once with ethanol and three times with deionized water, and finally dispersed in 25 mL of water for storage.

2.4 Preparation of three-dimensional LPCs. The above particle solution (6 mL) was collected by magnetic separation, and the supernatant was removed by centrifugation after adding ethanol to replace water. EG (100 μ L) and ethanol (1 mL) were added to the centrifuge tube, and the mixture was sonicated to fully disperse the particles. The system was placed in an oven at 60 °C for 18 h to evaporate ethanol, yielding a three-dimensional LPC with green structural color. The same procedure was repeated for different particle sizes and volumes: for 168 nm particles, 14 mL, 5.28 mL, 0.6 mL, and 0.18 mL samples were used; for 214 nm particles, 14 mL and 6 mL samples were used.

2.5 Fixation of Three-Dimensional LPCs. A three-dimensional LPC composed of 168 nm particles at a volume fraction of 20% was cured via a sol-gel method³⁰. A precursor mixture was prepared by sonicating 25 μ L of deionized water, 3 μ L of NH₃·H₂O (28%), 25 μ L of the colloidal suspension, and 75 μ L of EG. Then, 10 μ L of TEOS was added. After brief sonication, the system was left under a vertical magnetic field for 10 min to align the structure. Subsequently, 15 μ L of ammonia solution was added to solidify the aligned chains. The reaction proceeded for another 20 min, yielding solidified rod-shaped PCs. The same procedure was used for curing under a

90° magnetic field.

2.6 Optical Characterization of LPCs. LPC samples were dispersed into a custom-made quartz cuvette for optical measurements. Reflectance spectra were recorded using a fiber-optic spectrometer (HL2000-12). Optical measurements were performed with the incident light perpendicular to the sample surface, using the groove as the white background and the switched-off light source as the dark background. Optical images were captured using a micro-domain optical microscope (MICROWORLD, WSF400) or a smartphone camera. Magnetic fields were applied using a permanent magnet, with field strengths adjusted by varying the magnet-to-sample distance (Figure S5a) and orientations achieved by rotating the magnet. Figure S5(b) presents the magnetic field distribution and demonstrates that the field remained constant during magnet rotation. For perturbation experiments, mechanical disturbances were introduced by translating the cuvette coverslip or pressing capillary tubes with a glass slide. For the shearing experiments, 10 μL of the LPC dispersion was placed in a custom-made groove, forming a circular droplet with an area of $\sim 20 \text{ mm}^2$. Cyclic shearing was applied within 1 s, with a displacement of $\sim 5 \text{ mm}$ per cycle for 10 cycles. All tests were performed using 10 μL of sample in a 0.5 mm deep groove, with the magnetic field being the only variable.

2.7 Characterization. SEM (JEOL, REGULUS 81000) was used to characterize nanoparticle microstructures. TEM (JEOL, JEM-2100 F) was used for morphological characterization. Magnetization curves were obtained using a SQUID-VSM magnetic property measurement system. X-ray diffraction (XRD) patterns were recorded on a Rigaku SmartLab X-ray diffractometer, and phase identification was performed using MDI Jade 6 software by comparison with standard reference data.

3 Results and discussion

We first fabricated LPCs via an evaporation-induced supersaturation method²⁸ using $\text{Fe}_3\text{O}_4@\text{SiO}_2$ core-shell magnetic nanoparticles. Typically, a series of LPC samples using 168 nm particles at volume fractions of 37%, 18%, 5%, and 1.5% (samples 1-4), as well as 214 nm particles at volume fractions of 37% and 20% (samples 5-6) were

respectively constructed. As shown in Figure 1a-f, these samples exhibited structural colors spanning from blue, cyan, green, olive, yellow, to red. Reflectance spectroscopy confirmed that these colors originate from tunable photonic bandgaps, with peak wavelengths ranging from 452 nm to 661 nm (Figure 1g). To further elucidate the internal ordering, we solidified a 168 nm-based LPC via a sol-gel method and characterized its microstructure using scanning electron microscopy (SEM). The SEM image revealed a well-ordered face-centered cubic (fcc) stacking arrangement (Figure 1h), which represents the thermodynamically stable packing configuration. Besides, the corresponding Fourier transform diffraction pattern (Figure 1h, top-right inset) confirms a single-crystal domain within the observed region. Transmission electron microscopy (TEM) further confirmed the well-defined core-shell morphology of the constituent particles with sizes of 196@9 nm (total size: 214 nm) and 144@12 nm (total size: 168 nm), respectively (Figure 1i). Collectively, these results demonstrate that the synthesis and assembly approach yields high-quality LPCs with tunable structural colors spanning the full visible range, establishing a robust material platform for subsequent magnetic actuation studies. Additional characterization of the nanoparticles is provided in the Supporting Information (Figures S1-S3), including their uniform spherical morphology, preserved spinel crystal structure, and typical superparamagnetic behavior.

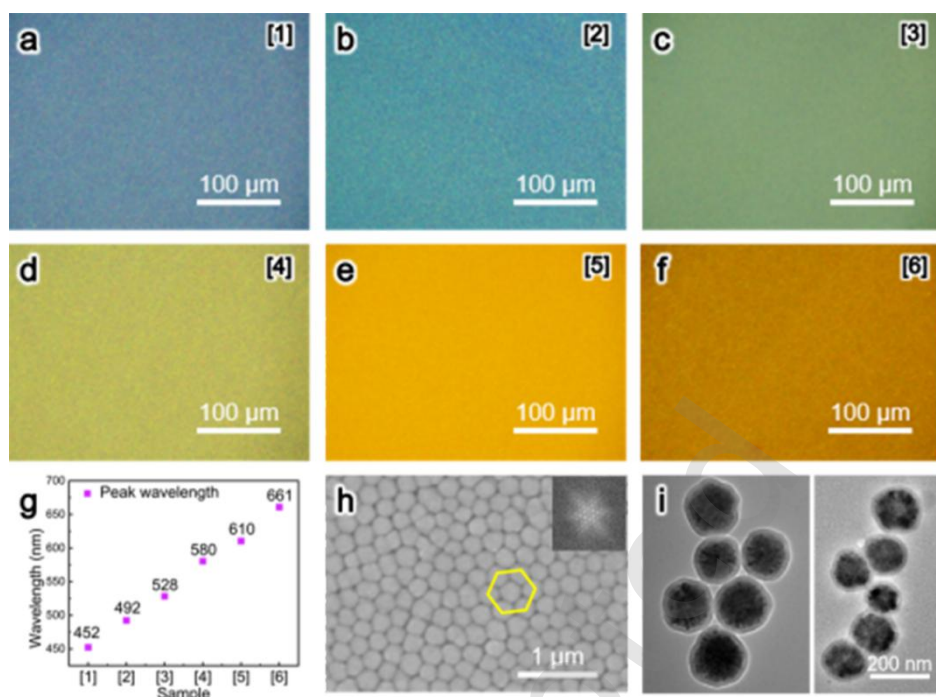


Figure 1. Construction and characterization of LPCs. Optical microscopy images of LPCs prepared by varied particle concentrations and sizes: (a) 37%, 168 nm; (b) 18%, 168 nm; (c) 5%, 168 nm; (d) 1.5%, 168 nm; (e) 37%, 214 nm; (f) 20%, 214 nm. (g) corresponding reflection peak wavelength for six samples sequentially shown in (a–f). (h) SEM image of the 168 nm-based LPC and the corresponding Fourier transform pattern (inset). (i) TEM images of 196@9 nm (214 nm) and 144@12 nm (168 nm) of magnetic nanoparticles used in the assemblies.

To investigate the effect of magnetic field on LPCs at varying particle concentrations, LPCs were prepared from 168 nm $\text{Fe}_3\text{O}_4@\text{SiO}_2$ nanoparticles at volume fractions of 20%, 5%, and 1%. In the absence of an external magnetic field, only the 20% sample exhibited a bright green structural color, attributable to ordered particle packing arising from balanced interparticle interactions at high concentration (Figure 2a). The 5% and 1% samples showed no vivid coloration, as the low particle density prevented ordered assembly (Figure 2b, c). Upon application of an 84 Gs magnetic field parallel to the incident light (0°), the 20% sample blue-shifted, while both the 5% and 1% samples displayed bright structural colors that were absent without the field (Figure 2d–f). Orienting the same field strength perpendicular to the incident light (90°) induced a pronounced red shift in all three samples (Figure 2g–i). Notably, the low-concentration samples also exhibited distinct chain-like structures

under the 90° orientation, confirming the establishment of three-dimensional PC architecture. As to their optical performances, the 20% sample showed a reflection peak near 510 nm without a field, which blue-shifted to 455 nm under 0° and red-shifted to 600 nm under 90° (Figure 2j). Meanwhile, the 5% and 1% samples exhibited field-induced emergence of reflectance peaks at 475 nm and 460 nm under 0° , with similar orientation-dependent shifts to 500 nm and 550 nm under 90° (Figure 2k-l). These results demonstrate that both magnetic field strength and orientation can modulate the optical response of LPCs, with field orientation enables switching between blue- and red-shifted states.

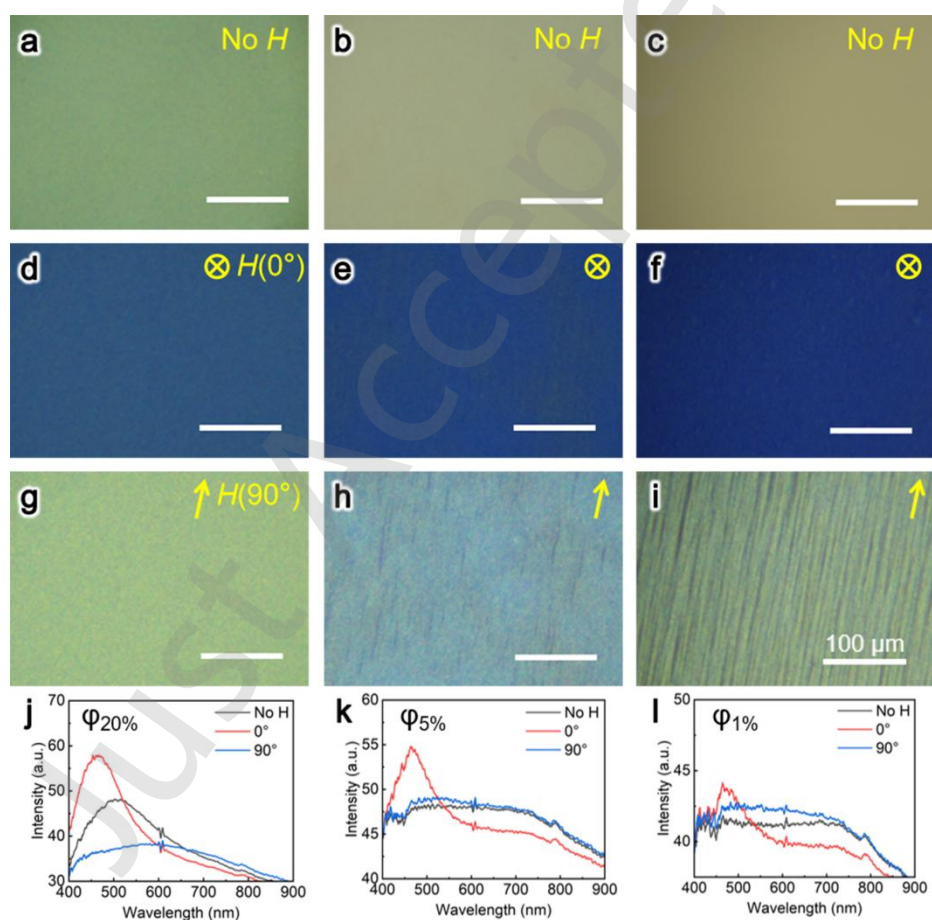


Figure 2. Magnetic-field modulation of LPCs at various particle concentrations (left column: 20%; medium column: 5%; right column: 1%). (a–c) Optical micrographs in the absence of an external magnetic field. (d–f) Optical micrographs acquired under a magnetic field (84 Gs) oriented parallel to the incident light (0°). (g–i) Optical micrographs acquired under a magnetic field of the same strength oriented perpendicular to the incident light (90°). (j–l) Corresponding reflectance spectra of the samples measured under the respective magnetic-field configurations.

We further investigated the microscopic mechanism underlying the orientation-dependent optical response. When a magnetic field is applied parallel to the incident light (0°), the magnetic force aligns the dipoles of adjacent nanoparticles along the field orientation, reducing the interparticle lattice spacing along the observation axis. This compression increases electrostatic repulsion between particles until a new equilibrium is established among magnetic force, long-range attraction, and electrostatic repulsion. Consequently, the assembly maintains a well-ordered structure while exhibiting a blue shift in its reflectance peak. When the magnetic field is rotated to 90° (perpendicular to the incident light), the assembled chains reorient by 90° to align with the new field orientation. As a result, the effective lattice spacing along the observation orientation increases, producing a red shift (Figure 3a). At 0° , the magnetic dipolar interaction between adjacent particles is attractive, reducing the lattice spacing, whereas at 90° , it becomes repulsive, increasing the lattice spacing.

³¹To directly visualize this field-induced structural reorganization, we solidified the LPCs via a sol-gel process while maintaining either a 0° or 90° magnetic field. As shown in Figures 3b-c, SEM images of the solidified samples reveal distinct lattice spacings. The structure assembled under a 0° field exhibited a lattice spacing of 220 nm (Figure 3b), whereas that under a 90° field showed 358 nm (Figure 3c), confirming that the orientation-dependent optical response originates from reconfigurable microscopic arrangements. In addition, we have provided statistical SEM images from additional sites in Figure S4. We have conducted statistical analysis of these SEM images. Quantitative measurements of lattice spacing and from >30 individual domains across multiple regions demonstrate that the structural response correlates consistently with the applied magnetic field orientation, further supporting the validity of our mechanistic interpretation. The statistical data are summarized in Table S2 (Supporting Information). We note that the structural evidence is derived from the SEM characterization of fixed samples. While the reproducibility across multiple regions and samples and quantitative statistical analysis supports the proposed mechanism. Direct observation of the liquid- state

structure during dynamic magnetic switching would be valuable for future investigation.

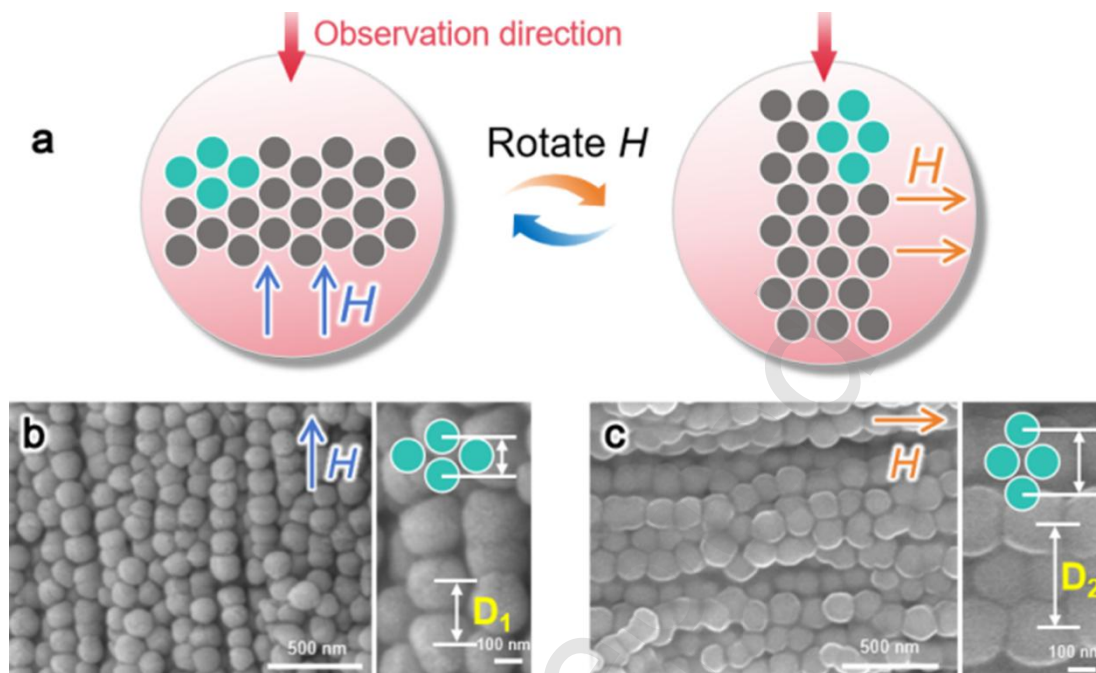


Figure 3. (a) Schematic illustration of particle arrangement under magnetic fields oriented at 0° (left) and 90° (right). (b, c) SEM images of the solidified PCs after curing under (b) 0° and (c) 90° magnetic fields.

We further examined how magnetic field strength modulates the structural color of LPCs as a function of particle size and concentration. Three representative systems involving 214 nm particles at a volume fraction (ϕ) of 37% ($S_{214}/\phi_{37\%}$), 168 nm particles at $\phi = 37\%$ ($S_{168}/\phi_{37\%}$), and 168 nm particles at $\phi = 20\%$ ($S_{168}/\phi_{20\%}$) were designed. For each system, reflectance spectra were recorded under increasing magnetic field strengths from 0 to 272 Gs (Figure 4a-c). Moreover, the relationships between the field strength and the peak wavelength and intensity are also quantitatively analyzed. Typically, for samples with the high volume fraction but different particle sizes ($S_{214}/\phi_{37\%}$ and $S_{168}/\phi_{37\%}$; Figure 4d-e), increasing the field strength induced a distinct blue shift in the reflection wavelength, accompanied by a gradual decrease in reflection intensity. As the magnetic field increases from 0 Gs to 272 Gs, the peak wavelength of $S_{214}/\phi_{37\%}$ varies from 661 nm to 615 nm, while that of $S_{168}/\phi_{37\%}$ shifts from 465 nm to 425 nm. It is noted that the magnitude of the blue shift is comparable between the two systems. Meanwhile, the peak intensity decreases

from 75% to 55% for $S_{214}/\phi_{37\%}$ and from 51% to 34% for $S_{168}/\phi_{37\%}$. This behavior is consistent with field-induced compression of the interparticle lattice spacing, which reduces the photonic bandgap wavelength while potentially introducing disorder that lowers reflectivity. In contrast, $S_{168}/\phi_{20\%}$ (Figure 4f) revealed a distinctly different intensity behavior. While the peak wavelength still blue-shifted 45 nm in the same field range, which was consistent with the other two systems, the reflection intensity exhibited a significant enhancement, increasing by approximately 22% from 0 to 272 Gs. This concentration-dependent discrepancy suggests that two competing mechanisms govern the intensity response. At high volume fractions, field-induced compression may disrupt the pre-existing ordered structure, leading to the reduction of reflectivity. At low volume fractions, where few ordered structures exist without a field, the magnetic field promotes particle assembly into ordered chains or clusters, thereby enhancing the structural color. Additionally, the strongest reflection peaks of $S_{214}/\phi_{37\%}$, $S_{168}/\phi_{37\%}$ and $S_{168}/\phi_{20\%}$ are respectively located at 661 nm (0 Gs), 465 nm (0 Gs), and 530 nm (171 Gs). This suggests that the lattice spacings of the highest-quality LPCs within the magnetic field range of 0-272 Gs are calculated to be 242 nm, 176 nm, and 213 nm, respectively, based on the Bragg diffraction equation (see Supporting Information for detailed derivations).

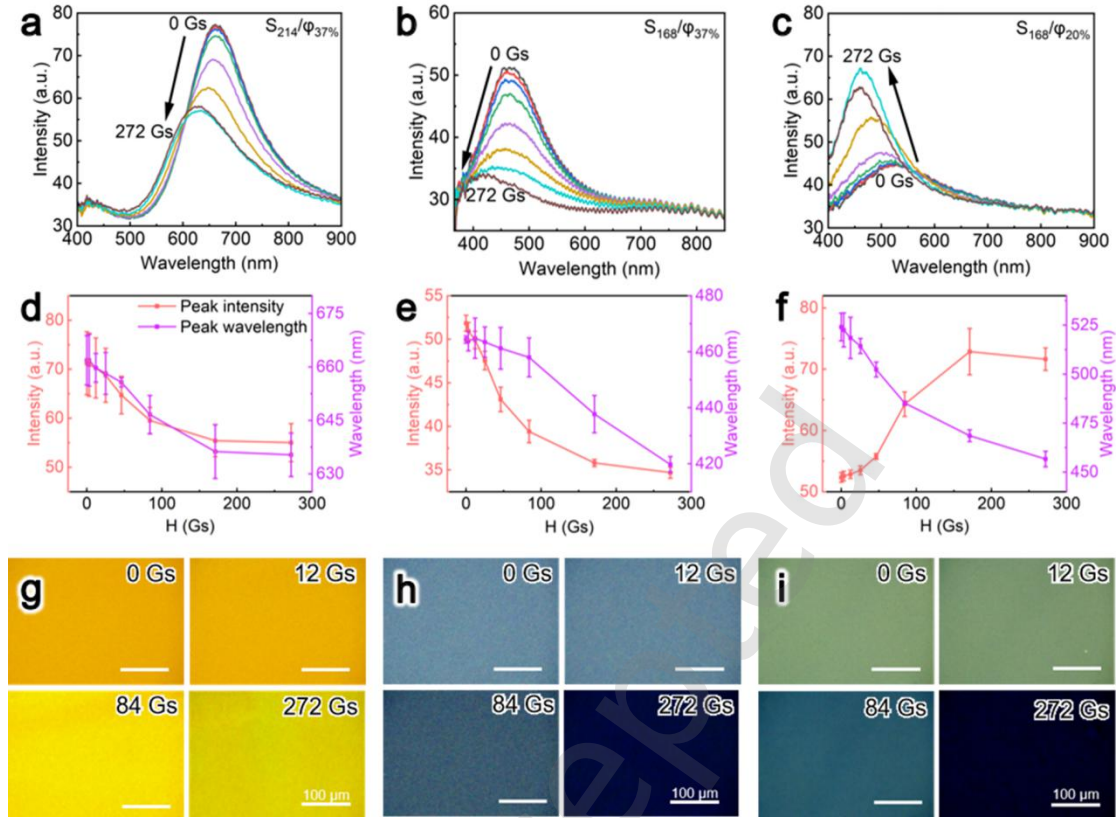


Figure 4. Modulation by Magnetic Field Strength. (a–c) Reflectance spectra of three LPCs ($S_{214}/\phi_{37\%}$, $S_{168}/\phi_{37\%}$, $S_{168}/\phi_{20\%}$) recorded under increasing magnetic field strength (0–272 Gs). (d–f) Corresponding variations in peak-wavelength and peak-intensity as a function of field strength derived from parallel experiments. (g–i) Corresponding optical micrographs captured at selected field strengths across the 0–272 Gs range.

Subsequent optical microscopy images reveal uniform and vivid structural colors both with and without an applied magnetic field, confirming that particle assembly occurs under both conditions (Figure 4g-i). Specifically, as the magnetic field is increased from 0 to 272 Gs, $S_{214}/\phi_{37\%}$ exhibits a color change from orange to light yellow, whereas $S_{168}/\phi_{37\%}$ shifts from blue to dark blue, and $S_{168}/\phi_{20\%}$ transitions from green to dark blue over the same range. In addition, we performed cyclic switching of the magnetic field and found that the switching could be completed within 1 s (Figure S6a). We also investigated the hysteresis during field ramping and observed that the switching could be accomplished within 0.25 s and remained stable thereafter (Figure S6b). Collectively, the progressive blue shift observed in the optical images aligns with the gradual blue shift seen in the reflectance spectra. These results demonstrate

that magnetic field strength controls both the peak wavelength (always blue-shifted) and the reflection intensity (enhanced or suppressed depending on the particle concentration), thereby establishing the first variable of our magnetic control strategy.

The orientation of the magnetic field provides an additional degree of freedom for modulating the optical response of the three-dimensional LPCs. Using the same three sample systems as in Figure 4, we fixed the field strength at 84 Gs and systematically rotated the field orientation from 0° to 90° with recorded reflection spectra (Figures 5a-c). Quantitative analysis of the peak wavelength and intensity with field orientation is summarized in Figures 5d-f. As the field orientation varied from 0° to 90° , the peak wavelength displayed a red shift trend across all samples owing to the increase of lattice spacings (Figure 3). For $S_{214}/\phi_{37\%}$ and $S_{168}/\phi_{37\%}$, rotating the field from 0° to 90° induced a substantial increase in reflection intensity (Figures 5d, e). In contrast, for $S_{168}/\phi_{20\%}$, the intensity showed a pronounced decreasing trend over the same angular range (Figure 5f). We attribute these opposing trends to differences in packing density. For high-volume-fraction samples ($\phi = 37\%$), rotation to 90° expands the lattice into a more open arrangement, allowing better ordering and enhanced intensity. For the low-volume-fraction sample ($\phi = 20\%$), the 0° field already induces optimal packing. Further rotation increases lattice spacing, reducing the coherence and decreasing intensity. Across the 0° - 90° field orientation range, the maximum reflection peaks for $S_{214}/\phi_{37\%}$, $S_{168}/\phi_{37\%}$, and $S_{168}/\phi_{20\%}$ are observed at 675 nm (at 90°), 463 nm (at 90°), and 487 nm (at 0°), respectively. Based on the Bragg equation, the corresponding optimal lattice spacings for the highest-quality LPCs are determined to be 247 nm, 175 nm, and 196 nm (Supporting information). In addition, we investigated the hysteresis during magnetic field rotation and found that the switching could be completed within 0.5 s and remained stable thereafter (Figure S6c). The ability to systematically tune the optical response by simply rotating the magnetic field further suggests the three-dimensional character of the LPC lattice and underscores the versatility of our dual-variable magnetic modulation strategy.

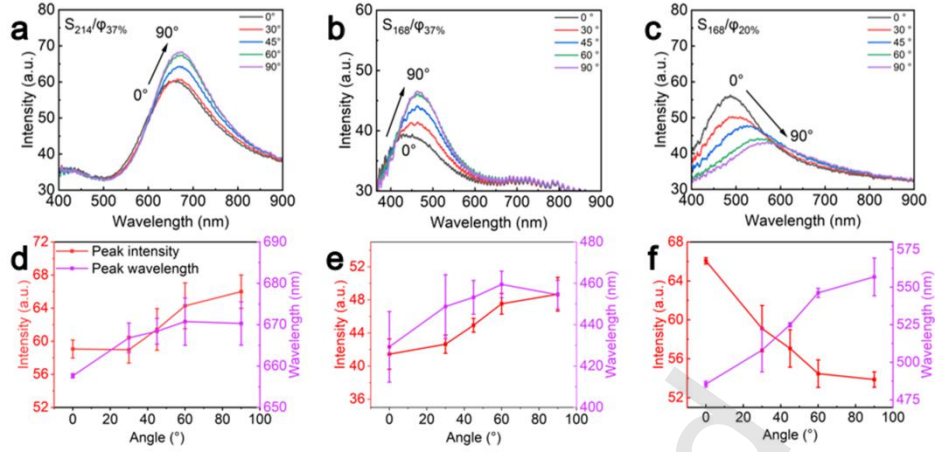


Figure 5. Control via Magnetic Field Orientation. (a–c) Reflectance spectra of three LPCs (S₂₁₄/φ_{37%}, S₁₆₈/φ_{37%}, and S₁₆₈/φ_{20%}) recorded under a fixed field strength of 84 Gs as the field orientation was rotated from 0° to 90° relative to the incident light. (d–f) Corresponding variations in peak-wavelength and peak-intensity as a function of field angle derived from parallel experiments.

To demonstrate the practical utility in display, we fabricated capillary-confined LPC patterns using two representative samples: S₂₁₄/φ_{37%} (red) and S₁₆₈/φ_{20%} (green). An “XCC” pattern was constructed with the red sample filling one “C” and the green sample filling the other. Smartphone images show vivid structural colors even without magnetic field, and a clear blue shift upon application of a 171 Gs of magnetic field (Figure 6a). Optical microscopy confirms that the red “C” shifts to yellow and the green “C” shifts to blue (Figures 6b-e), demonstrating real-time magnetic tuning. We further evaluated mechanical stability under external perturbation. As shown in Figure 6f-g, we performed ten measurement cycles; we defined the initial reflectance of each cycle as I_0 and the reflectance after mechanical shearing as I , and calculated $|I - I_0|$ as the fluctuation value to evaluate the effect of the magnetic field on the mechanical shearing. The calculated results show that the average fluctuation of the reflected intensity was $|I - I_0| = 7.1$ in the absence of a magnetic field, but decreased to 0.2 when the field was applied. Subsequent smartphone images of the green “C” element under compression visually confirm this stabilization. The structural color is visibly disrupted without a magnetic field (Figure 6h) but remains vivid and uniform with the magnetic field (Figure 6i). A schematic diagram of the pressure experimental setup is

provided in Figure S7. These demonstrations highlight the combination of real-time tunability and mechanical stability offered by the magnetically responsive LPC platform.

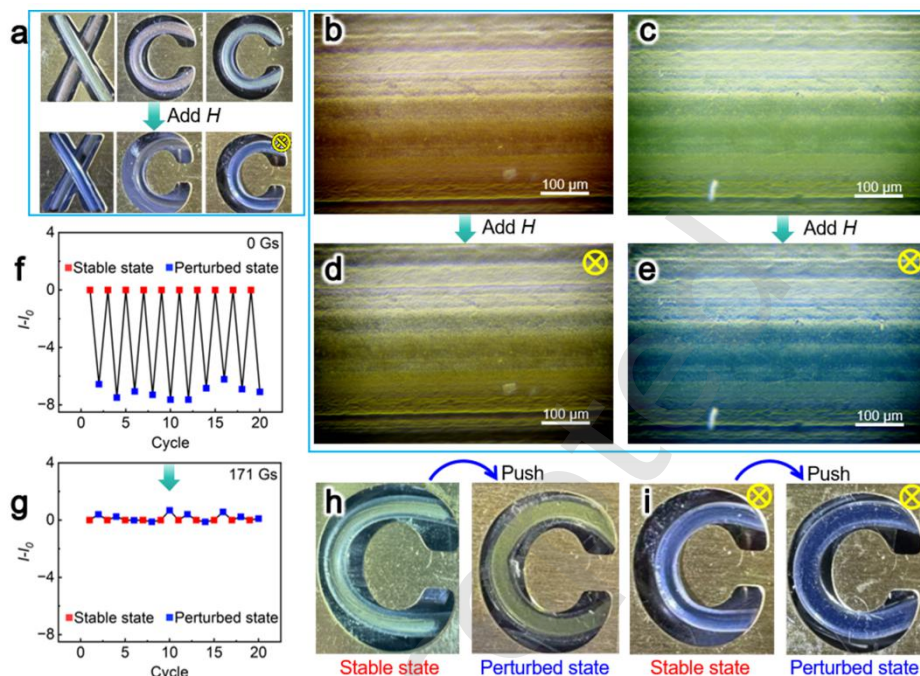


Figure 6. Display application and resistance to mechanical shear force capability of LPCs. (a) Photographs of an “XCC” patterned capillary platform filled with two LPC samples ($S_{214/\phi 37\%}$ in red and $S_{168/\phi 20\%}$ in green), captured before and after applying a 171 Gs magnetic field. (b-c) Optical micrographs of the red and green “C”-shaped elements before (top) application of a 171 Gs magnetic field. (d-e) Optical micrographs of the red and green “C”-shaped elements after (bottom) application of a 171 Gs magnetic field. (f-g) Relative change in reflectance peak intensity ($I - I_0$) during mechanical perturbation without (top) and with (bottom) a 171 Gs magnetic field. Smartphone images of the green ($S_{168/\phi 20\%}$) “C” element under mechanical shear force without (h) and with (i) an applied magnetic field, highlighting the field-induced stabilization against external disturbance.

4 Conclusions

In summary, we have developed magnetic nanoparticle-based LPCs that integrate full-visible-spectrum structural coloration, dual-variable magnetic modulation, and mechanically stabilized display performance. By systematically tailoring particle size and concentration, we achieved three-dimensional LPCs with structural colors spanning the entire visible region. Subsequently, a dual-variable magnetic modulation

strategy involving field strength (0-272 Gs) and field orientation (0°-90°) was introduced to modulate the optical responses. SEM images of the fixed LPCs revealed distinct particle arrangements under 0° and 90° fields, confirming that the orientation-dependent optical response originates from reconfigurable microscopic structures. Notably, this magnetic field orientation modulation was realized in three-dimensional LPCs assembled from isotropic magnetic nanoparticles, offering a dual-variable magnetic modulation from strategies that rely on anisotropic particle design. Moreover, the magnetically induced LPCs exhibit substantially enhanced mechanical stability compared to their non-field-induced state counterparts, which is a mechanically stabilized behavior critical for practical applications. Leveraging this capability, we demonstrated mechanically stabilized display using capillary-confined LPCs, which exhibit reversible color switching under magnetic actuation while maintaining optical signal integrity under external compression. Collectively, this work establishes a versatile platform that bridges static LPC fabrication and dynamic dual-variable magnetic modulation, opening new avenues for adaptive displays, anti-counterfeiting, and mechanically robust optical sensing systems.

Electronic Supplementary Material: Comparison between our work and other reported studies. Statistical data for field-angle switching. SEM image of magnetic nanoparticles with total sizes of 168 nm and 214 nm. XRD pattern of Fe₃O₄@SiO₂ nanoparticles. Hysteresis loops of Fe₃O₄@SiO₂ nanoparticles. The particle arrangements were characterized by SEM imaging of multiple regions and samples. Relationship between the magnet – sample distance and the magnetic field strength. Schematic illustration of the magnetic field distribution as a function of field orientation, along with the magnet geometry. Cyclic switching of the magnetic field was performed within 1 s. The hysteresis behavior upon field ramping was characterized. The hysteresis behavior upon field orientation rotation was characterized. Calculation of lattice spacing for three types of LPCs under varying magnetic field strength and orientation. Schematic diagram of pressure application in a capillary tube.

Data availability

All data needed to support the conclusions in the paper are presented in the manuscript and/or the Electronic Supplementary Material. Additional data related to this paper may be requested from the corresponding author upon request.

Acknowledgments

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Declaration of competing interest

All the contributing authors report no conflict of interests in this work.

Author contribution statement

C. C. X.: Data curation, project administration, validation, writing manuscript, experimental design. Y. H. W.: Data curation. C. C. L.: Data curation. M. L. W.: Data curation. Y. H. S.: Data curation. F. L. J.: Data curation. F. L. Q.: Data curation, project administration, writing manuscript, experimental design, funding acquisition. C. F. D.: Data curation, project administration, writing manuscript, experimental design, funding acquisition. All the authors have approved the final manuscript.

Use of AI statement

None.

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Electronic Supplementary Material

Liquid photonic crystals enabling dual-variable magnetic modulation and mechanically stabilized display

Chunchao Xu,¹ Yonghao Wang,¹ Chengcheng Liu,¹ Menglei Wang,^{2,3} Youhao Sun,¹ Fulin Jia,³

Fenglian Qi ^{1,*} and Caifeng Ding ^{1,*}

1 Key Laboratory of Optic-electric Sensing and Analytical Chemistry for Life Science, Shandong Key Laboratory of Analytical Chemistry for Life Science and Intelligent Detection, College of Chemistry and Molecular Engineering, Qingdao University of Science and Technology, Qingdao 266042, China

2 Green Catalysis Center, and College of Chemistry, Zhengzhou University, Zhengzhou 450001, China

3 CAS Key Laboratory of Nanosystem and Hierarchical Fabrication, CAS Center for Excellence in Nanoscience, National Center for Nanoscience and Technology, Beijing 100190, China

✉ Address correspondence to Fenglian Qi, qifenglian@qust.edu.cn; Caifeng Ding, dingcaifeng@qust.edu.cn

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Samples	3D-PC ¹	3D-PC ²	1D-PC ^{3,4,5}	3D-PC (Our work)
Building block	Fe ₃ O ₄ @SiO ₂	SiO ₂	Fe ₃ O ₄	Fe ₃ O ₄ @SiO ₂
	colloidal nanocluster	nanosphere	colloidal nanocluster	nanoparticle
Response type	Magnetic response	Mechanical shear	Magnetic response	Mechanically stabilized magnetic response
Concentration	0.10-0.12%	0.06-0.24%	0.06%	0.01-0.37%
Magnetic modulation approach	Field strength	——	Field strength	Field strength and direction

Table S1. Comparison between our work and other reported studies.

0°									
0.136	0.155	0.123	0.124	0.138	0.153	0.136	0.109	0.114	0.143
0.128	0.123	0.132	0.158	0.152	0.177	0.147	0.144	0.134	0.166
0.143	0.153	0.132	0.151	0.155	0.155	0.174	0.133	0.151	0.182
90°									
0.299	0.284	0.272	0.249	0.259	0.321	0.257	0.296	0.309	0.31
0.301	0.312	0.299	0.33	0.306	0.318	0.28	0.302	0.295	0.313
0.298	0.324	0.272	0.245	0.272	0.272	0.265	0.325	0.28	0.267

Table S2. Statistical data for field-angle switching.

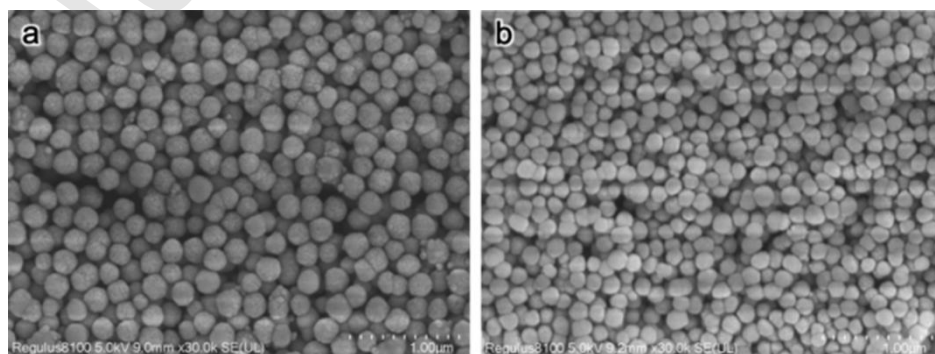


Figure S1. SEM images of Fe₃O₄@SiO₂ nanoparticles with total size of (a) 214 nm and (b) 168 nm.

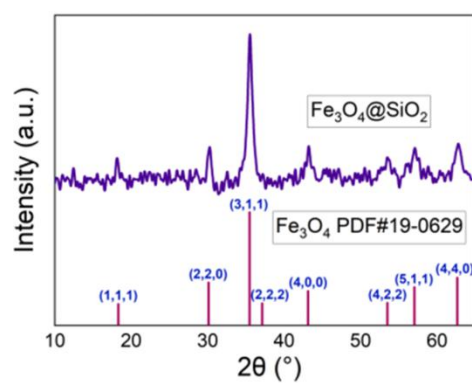


Figure S2. XRD pattern of 168-nm $\text{Fe}_3\text{O}_4@\text{SiO}_2$ nanoparticles.

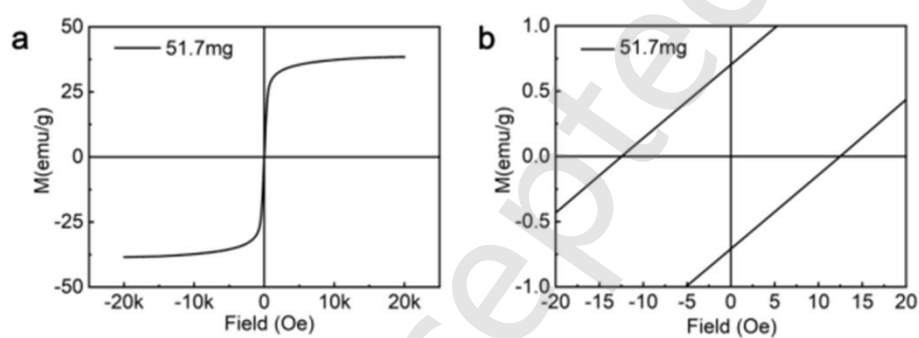


Figure S3. Hysteresis loop of 168-nm $\text{Fe}_3\text{O}_4@\text{SiO}_2$ nanoparticles.

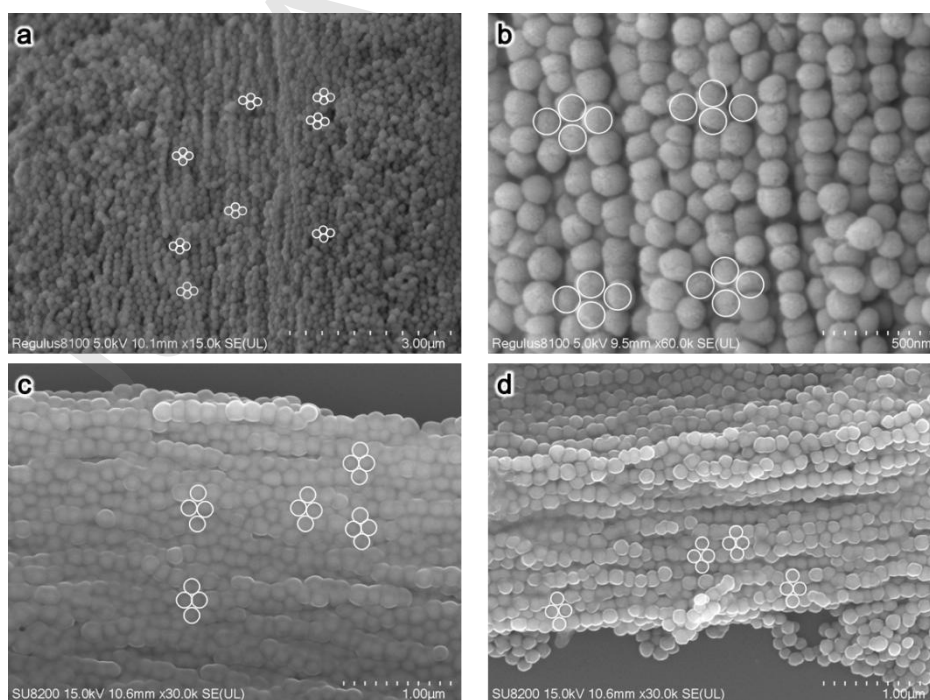


Figure S4. The particle arrangements were characterized by SEM imaging of multiple regions and samples.

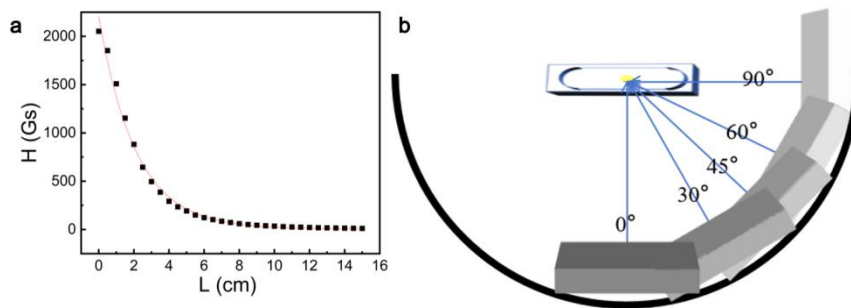


Figure S5. (a) Relationship between the magnet–sample distance and the magnetic field strength. (b) Schematic illustration of the magnetic field distribution as a function of field orientation, along with the magnet geometry.

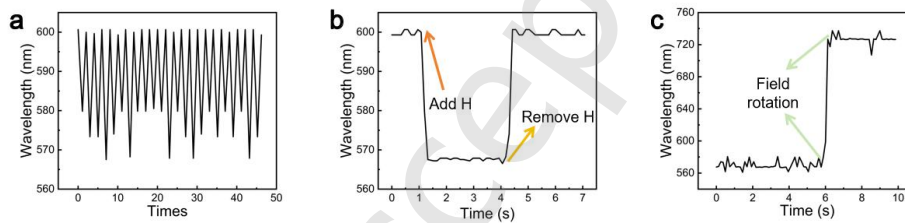


Figure S6. (a) Cyclic switching of the magnetic field was performed within 1 s. (b) The hysteresis behavior upon field ramping was characterized. (c) The hysteresis behavior upon field orientation rotation was characterized.

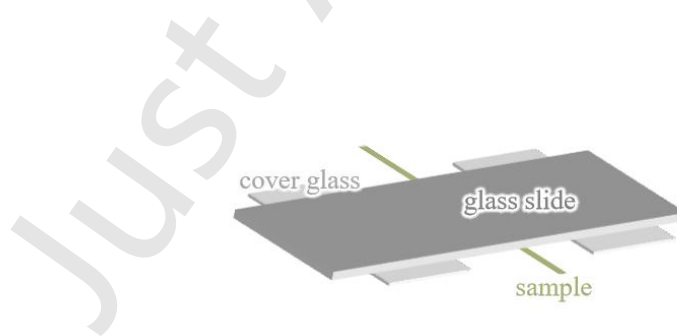


Figure S7. Schematic diagram of pressure application in a capillary tube.

1. Calculation of the lattice spacing of LPCs.

The lattice spacing of LPCs was calculated using the Bragg diffraction formula for fcc stacking configurations (eq 1)².

$$m\lambda = (8/3)^{0.5} \cdot D \cdot n_{total} = 1.633 \cdot D \cdot n_{total} \quad (1)$$

Where m is the diffraction order, λ is the reflected wavelength, and n_{total} is the average refractive index of the LPC. In this work, $m=1$, and λ was directly obtained from the reflection spectrum. The value of n_{total} was calculated based on the refractive indices and volume fractions of each component (eq 2)²:

$$n_{total} = \phi_{Fe_3O_4 @ SiO_2} \cdot n_{Fe_3O_4 @ SiO_2} + \phi_{EtOH} \cdot n_{EtOH} + \phi_{EG} \cdot n_{EG} \quad (2)$$

The refractive index of the $Fe_3O_4 @ SiO_2$ particles was further calculated from the volume fractions and refractive indices of the Fe_3O_4 core and the SiO_2 shell (eq 3):

$$n_{Fe_3O_4 @ SiO_2} = f_{core} \cdot n_{Fe_3O_4} + f_{shell} \cdot n_{SiO_2} \quad (3)$$

To account for residual ethanol after evaporation, the remaining ethanol volume was determined gravimetrically. The initial mixture containing particles, ethanol, and ethylene glycol was weighed (m_0), then dried at 60 °C for 18 h. After drying, the residual mass (m_r) was recorded. Evaporation of ethylene glycol (bp 197.3 °C) under these conditions was negligible. The residual ethanol volume (v_r) was then calculated from the mass loss and the density of ethanol (eq 4):

$$v_r = v - v_0 = v - (m_0 - m_r) / \rho_{EtOH} \quad (4)$$

Under zero magnetic field (0 Gs), the $S_{214}/\phi_{37\%}$ particles exhibited a reflection maximum at 661 nm. Applying the Bragg diffraction formula (eq 1), the corresponding optimal lattice spacing (D_{opt}) was calculated to be 242 nm. Similarly, for the $S_{168}/\phi_{37\%}$ particles at 0 Gs, the reflection peak appeared at 465 nm, yielding $D_{opt}=176$ nm. In contrast, the $S_{168}/\phi_{20\%}$ particles under a 171 Gs field showed a peak at 530 nm, corresponding to $D_{opt}=213$ nm (Figure 4a-c).

For the 90° field orientation, the calculated D_{opt} are as follows: $S_{214}/\phi_{37\%}$ ($\lambda=675$ nm) gave $D_{opt}=247$ nm; $S_{168}/\phi_{37\%}$ ($\lambda=463$ nm) gave $D_{opt}=175$ nm; and $S_{168}/\phi_{20\%}$ at 0° ($\lambda=487$ nm) gave $D_{opt}=196$ nm (Figure 5a-c).

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