Dynamic Tuning of Optical Transmittance of 1D Colloidal Assemblies of Magnetic Nanostructures

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Smart materials with switchable optical properties may find interesting applications in designing advanced intelligent systems. Herein, the dynamic tuning of optical transmission is reported by controlling the orientation of 1D colloidal assemblies of magnetic nanostructures. Colloidal magnetic nanostructures of Fe₃O₄, including nanospheres, nanorods, and nanodiscs, are assembled into 1D chains under external magnetic fields. Magnetic tuning of the orientation of the nanochains results in a pronounced contrast in optical transmittance, which is strongly dependent on the size and shape of the primary nanostructures. Contrary to the intuitive expectation, the 1D chains of the nanospheres and nanorods exhibit lower transmittance when they are oriented parallel rather than perpendicular to the incident light, whereas the nanodisc counterpart responds oppositely due to the unique “edge-to-edge” assembly mode of the nanodiscs. The dynamic tuning of the optical transmittance through magnetic means is believed to have broad applications in the design of novel switchable optical devices. As an example, the incorporation of orientation-dependent optical properties of 1D chains into the construction of intelligent polymer films with their transparency sensitive to rotation and bending is demonstrated.

1. Introduction

Smart optical materials are of broad scientific and technological significance due to their tunable, switchable, and adaptive optical properties and functions,[1] which show many advantages over traditional optical components.[2] They respond to a variety of environmental stimuli, such as magnetic fields,[3] thermal activation,[4] photoluminescence, and electric fields,[5] which can be used to construct antiglare mirrors, smart windows, information display, sensors, etc.[6] The tunable optical properties include light absorption,[7] scattering,[8] reflectivity,[9a,8] luminescence,[10a,9] etc.[3c,9]

Among various external environmental stimuli, magnetic fields have been extensively studied due to its eco-friendliness, smooth operation, reversibility, rapid response, and low cost.[11] Actively tuning the strength and directions of magnetic fields has been proved as an effective way to remotely manipulate the orientation and assembly of magnetic colloidal particles in various dispersions. As a result, the rheological, thermal, and optical properties of the colloidal dispersions can be quickly and reversibly controlled using an external magnetic field.[11] In addition to magnetic nanoparticles, magnetic fields can also be used to actively tune the physical properties of magnetic/non-magnetic composite materials, leading to a variety of interesting applications.[12] For instance, the combination of an anisotropic magnetic Fe₃O₄@SiO₂ microrod core and a luminescent metal–organic framework shell produces an intelligent optical composite material with switchable optical properties, which can be tailored continuously between isotropic red emission and anisotropic reflection of light.[13] In addition, the magnetic tuning of the plasmonic excitation of Au nanorods has also been achieved by attaching Au nanorods to Fe₃O₄ nanorods whose orientation can be magnetically controlled.[9a] Furthermore, the incorporation of magnetic responses into 2D microstructures is of particular interest because magnetic interactions can provide a reliable way to control their anisotropic physical properties.[6a] Highly reflective gold microplates or silver nanoplates decorated with magnetic Fe₃O₄ nanoparticles can be rapidly rotated by a magnetic field and exhibit strong contrast in reflectance or transmittance.[6a,11]

Herein, we investigate the dynamic tuning of the optical transmittance of oriented 1D chain-like assemblies using magnetic Fe₃O₄ 0D nanospheres, 1D nanorods, and 2D nanodiscs as building blocks. Contrary to the intuitive expectation, the chains of nanospheres and nanorods exhibit low transmittance when their orientation is parallel to the incident angle of light. Conversely, more visible light passes through the dispersions when the
orientation of the chains is perpendicular to the incident light. Interestingly, we found that the nanodisc chains behave just the opposite: their optical transmittance is higher when the chain orientation is parallel rather than perpendicular to the incident light. Our results demonstrate the importance of nanoparticle shapes on the colloidal assembly as well as the optical properties of the assembled 1D chains. The active tuning of the optical transmittance by magnetic fields and structure-dependent optical properties offer many new opportunities for designing smart optical devices in real-world applications.

2. Results and Discussion

To study the effect of nanoparticle morphology on the optical properties of their assemblies, we first synthesized Fe₃O₄ nanospheres, nanorods, and nanodiscs based on previously reported procedures.[12] Figure 1a shows the transmission electron microscopy (TEM) image of Fe₃O₄ nanospheres (∼115 nm in diameter) coated with a layer of SiO₂ (∼20 nm in thickness). The thin SiO₂ layer was deposited through a sol–gel process to enhance the chemical stability and colloidal dispersity of the Fe₃O₄ nanospheres.[13] For the Fe₃O₄@SiO₂ nanorods shown in Figure 1b, the major and minor axes of Fe₃O₄@SiO₂ nanorods are ∼400 and 80 nm, respectively, and the thickness of the SiO₂ coating is about 5 nm. The size and structure of the nanorods are uniform with an aspect ratio (AR) of about 5. The structure of the nanodiscs is a regular hexagon (Figure 1c). The average diagonal length of the Fe₃O₄ nanodiscs is 300 nm, and the thickness of the nanodiscs is 20 nm. The thickness of the SiO₂ coating is ∼10 nm, resulting in an overall AR of about 8.

The hysteresis loops of three kinds of Fe₃O₄@SiO₂ nanoparticles were investigated by characterizing the field-dependent magnetization (Figure S1, Supporting Information). For Fe₃O₄@SiO₂ nanospheres, they are superparamagnetic with a magnetic saturation (Mₛ) of ∼17.5 emu g⁻¹, which is smaller than the Fe₃O₄ nanospheres without SiO₂ shell in our previous work.[14] Fe₃O₄@SiO₂ nanorods and nanodiscs are ferromagnetic with an Mₛ and a coercivity of 16.9 emu g⁻¹ and 79 Oe for rods and 20.3 emu g⁻¹ and 181 Oe for discs. Due to the SiO₂ shell, the Mₛ values of the Fe₃O₄@SiO₂ nanorods and nanodiscs are also smaller than those without SiO₂ shell.[12,14]

For anisotropic nanomaterials, actively tuning their optical properties by applying different environmental stimuli is highly desirable for preparing smart materials. In principle, magnetic nanostructures can be assembled into chains by applying a magnetic field, and thereby, their orientation can be effectively controlled by the direction of applied fields due to their preferential parallel alignment, providing a reliable way to reversibly and instantaneously modulate the optical transmittance and contrast of their colloidal dispersions. We chose magnetic Fe₃O₄ nanospheres as starting materials, which were synthesized through a hydrothermal method reported previously.[1c,12a] For Fe₃O₄ nanospheres, nanorods, and nanodiscs, they will be assembled into chains when a magnetic field is applied. Figure 1d,e shows the optical microscopy images of Fe₃O₄@SiO₂ nanodiscs under the horizontal and vertical magnetic fields, respectively. The 1D chain-like structures were observed when the colloidal dispersions of nanodiscs were exposed to a magnetic field. The obtained 1D nanochains exhibited obvious magnetic anisotropy due to the dipole–dipole coupling between neighboring building blocks, resulting in parallel alignment to the field directions. Therefore, they can be easily aligned along the arbitrary directions on demand by applying a magnetic field (Figure S2, Supporting Information). Video 1, Supporting Information, indicates that the orientation of Fe₃O₄ nanodisc chains can be rapidly adjusted by changing the magnetic field directions. Because a droplet of the sample solution was sandwiched between two glass slides to facilitate optical observation, the chains formed in the confined spaces were short. As shown in Video 2, Supporting

![Figure 1](http://www.advancedsciencenews.com/)

Figure 1. a–c) TEM images of a) Fe₃O₄@SiO₂ nanospheres, b) Fe₃O₄@SiO₂ nanorods, and c) Fe₃O₄@SiO₂ nanodiscs. d,e) Optical microscopy images of Fe₃O₄@SiO₂ nanodisc under different magnetic field directions. f) TEM image of assembled 1D chains of Fe₃O₄@SiO₂ nanodiscs.
Information, when a droplet of the sample solution was directly placed on a glass substrate, the length of the chains was larger, and the rotation of the chains was more accurately manipulated under the applied magnetic fields. However, the optical image is not very clear but somewhat blurred because of the random scattering at the water–air interfaces and the Brownian motion of colloidal particles. To understand how the nanoparticles are assembled under a magnetic field, we present a convenient and flexible approach for the fabrication of individually fixed nanochains by combining magnetic assembly with sol–gel processes.\textsuperscript{[15]} The nanospheres are arranged into 1D nanochains under magnetic fields (Figure S3a, Supporting Information). In the case of nanorods, they are arranged in a “head-to-head” manner in the 1D nanochains due to the preferential magnetization along the long axes (Figure S3b, Supporting Information). Similarly, due to easy magnetization along the radical directions, the nanodiscs are assembled in an “edge-to-edge” manner rather than a “face-to-face” manner in the magnetic fields (Figure 1f).

Contrary to the intuitive assumption that there should be more light passing through the dispersions when the chains are parallel to the beam path, the colloidal dispersions of nanospheres or nanorods have a higher transmittance as the orientation of the chains is perpendicular to the incident beam. As shown in Figure 2, the transmittance of the colloidal dispersions of Fe\textsubscript{3}O\textsubscript{4} nanoparticles can be actively tuned by changing the magnetic field directions, which can be easily observed by the naked eyes at ambient conditions. For Fe\textsubscript{3}O\textsubscript{4} nanospheres (Figure 2a), their colloidal dispersions were almost opaque with a dark brown color when the applied magnetic fields were parallel to the viewing directions (0°). While the magnetic field was rotated to 90°, the dispersions immediately became translucent, indicating a higher transmittance (Figure 2b). As shown in Figure 2c, the optical transmittance of the Fe\textsubscript{3}O\textsubscript{4} nanosphere dispersion is strongly dependent on the angles of the applied magnetic fields. The light was incident along the y-axis, and the nanochains were rotated in the x–y plane. Interestingly, when the orientation of the chains was parallel to the direction of the incident light (0°), the optical transmittance of the Fe\textsubscript{3}O\textsubscript{4} nanosphere dispersion was low. In contrast, when the orientation of the chains was perpendicular to the direction of incident light (90°), the optical transmittance of the nanosphere sample was high. Moreover, the spectral profile suggests a wavelength-dependent transmittance of the colloidal dispersions: higher at a longer wavelength and lower at a shorter wavelength. It is also interesting to point out that the optical transmittance increases dramatically from 0° to 45°, followed by negligible changes from 45° to 90°. The optical properties of colloidal dispersions of nanorods are similar to those observed in nanospheres (Figure 2d,e). Notably, the colloidal dispersions of both nanospheres and nanorods could be reversibly tuned between opaque at 0° and translucent at 90° by simply changing magnetic field directions. In terms of spectra, we observed a similar wavelength- and orientation-dependent transmittance in Fe\textsubscript{3}O\textsubscript{4} nanospheres (Figure 2c) and nanorods (Figure 2f). The transmittance of colloidal dispersions of nanorods increased from 0° to 30° and remained unchanged from 30° to 90°. In addition, it can be seen that the tunable transmittance range for the nanorods between 0° and 90° is smaller than that for the nanospheres. Nevertheless, when 1D chains were assembled using 2D nanodiscs, the optical performances were completely different. As shown in Figure 2g,h, the Fe\textsubscript{3}O\textsubscript{4}...
nanodisc dispersions became near transparent at 0° and turned into opaque with a brownish-black color when the magnetic field angle was rotated to 90°. Although nanodiscs may rotate along the easy axis of magnetization, they can still exhibit excellent contrast between parallel and perpendicular directions due to their unique 2D anisotropy and “edge-to-edge” assembly. In addition, the optical properties of the nanodisc dispersions in a glass vial can be easily and reversibly switched between the “on” (transparent) and “off” (opaque) states by changing the directions of the applied magnetic fields (Video 3, Supporting Information).

Surprisingly, as shown in Figure 2i, the dependence of transmittance of nanodisc dispersions on the magnetic field directions was opposite to that of nanospheres and nanorods. More specifically, the optical transmittance of the Fe₃O₄ nanodisc dispersions decreased when the angle was increased from 0° to 45°, and then remained unchanged from 45° to 90° in the visible range. Furthermore, the transmittance of the nanodisc dispersions decreased with increasing wavelength at 0°. When the magnetic field was rotated to 90°, the transmittance increased continuously with the wavelength of the incident light. By comparing the optical spectra of nanospheres, nanorods, and nanodiscs, we conclude that the optical tunability in the case of nanodiscs is much larger than the other two samples, which is closely related to the structural characteristics of the building blocks and, thereby, different assembled behaviors under magnetic fields.

To further understand the optical properties of the 1D chains assembled from different Fe₃O₄ nanostructures, we measured the optical transmittance of the colloidal dispersions of chains with three typical orientations under polarized light. The light was incident along the y-axis and polarized along the z-axis.

When the orientation of the chains is parallel to the light beam path, it is marked as 0°. When the orientation of the chains is orthogonal to the light beam path and the polarization direction of the light, it is marked as 90°–90°. In the third case, the orientation of the chains is perpendicular to the light beam path but parallel to the light polarization directions, and it is marked as 90°–0°. For the Fe₃O₄ nanospheres (Figure 3a,b), the optical transmittance decreased when magnetically switching the chain orientation from 90°–90° to 90°–0° and finally 0°. According to the theoretical calculations in the literature,[16] the intensity of the scattered light is angle-dependent when a plane wave of incident light is illuminated on a linear array of nanospheres, and the mean distance between the nanospheres is less than half of the incident wavelength. The linear array of nanospheres exhibits lower transmittance when it is oriented parallel rather than perpendicular to the incidence of light.[16] As the size of nanospheres used in our experiments (~155 nm) is less than the half wavelength of visible light, the transmittance of the nanosphere chains was high in the perpendicular case and low in the parallel case, making our experimental observation consistent with the theoretical predictions.

In the case of 0°, the multiple scattering occurs at nanospheres in the chains, which could greatly attenuate the intensity of transmitted light. The transmittance results for Fe₃O₄ nanospheres under polarized light are consistent with that measured under ordinary light (Figure 2c). Similar to the case of Fe₃O₄ nanospheres, the optical transmittance of the colloidal dispersions of Fe₃O₄ nanorods was high at 90°–90° and low at 0° (Figure 3c,d). This is probably because of the head-to-head assembly of spindle-shaped nanorods under magnetic fields and the induced similarities in the...
geometric symmetry and magnetic anisotropy of 1D chains of nanospheres and nanorods. For the Fe$_3$O$_4$ nanodiscs (Figure 3e,f), because their lateral dimension (≈320 nm) is larger than the half wavelength of most visible light, the optical transmittance of the assembled chains does not follow the theoretical prediction. Instead, we found that the chains of nanodiscs look more like nano shutters and behave like the window blinds in interaction with light due to their high AR (≈8). In addition, compared with the cases of nanospheres and nanorods, the increases in scattering cross sections of 1D nanodisc chains are much larger when their orientation is switched from parallel to perpendicular direction. Therefore, it is easier for light with short wavelengths to pass through the channel, and the transmittance of the colloidal dispersions of nanodiscs is highest when the chains are parallel to light incidence (0°). In the case of 90°–0°, because short-wavelength light is scattered and absorbed by iron oxide, its intensity decays significantly when passing through the colloidal dispersions, resulting in low transmittance. Notably, the optical transmittance in the case of 90°–0° is lower than that of 90°–90° not only for nanodiscs but also for nanospheres and nanorods. When the chains are parallel to the polarization of light (90°–0°), there will be a strong interaction between photons and atoms, thus resulting in strong scattering and absorption and low transmittance of light. To ensure the parallel alignment of chains in the solutions, the samples were placed in the center of the right front of a permanent magnet (Figure S4, Supporting Information).

Based on our systematic studies, we have demonstrated that the optical properties of the assembled 1D chains are strongly dependent on not only the orientations of chains but also the shapes of the building blocks. The chains of nanodiscs have the best optical contrast between the parallel and perpendicular directions when compared with that of nanospheres and nanorods. More importantly, nanodiscs are primarily assembled in an “edge-to-edge” manner rather than a “face-to-face” manner (Figure 1f), which can exhibit excellent contrast under applied magnetic fields of different orientations. To further investigate the optical modulation of the nanodiscs, we then measured the optical transmittance of the colloidal dispersions of the Fe$_3$O$_4$ nanodiscs under different distances from the magnet and duration. When the orientation of the chains is parallel to the light beam path, the distance has a significant influence on the optical transmittance (Figure 4a). The optical transmittance decreased in the visible range with the increase in distance from 5 to 30 cm. In addition, the optical transmittance decreased in the visible range as the wavelength increased when the distance was less than 20 cm. The distance between the sample and the magnet is closely related to the magnetic field strength,  

![Figure 4](image_url). The dependence of optical transmittance spectra of colloidal dispersions of Fe$_3$O$_4$ nanodiscs on the a,b) magnet-sample distance and c,d) field duration. The magnetic field was oriented a,c) parallel or b,d) perpendicular to the light incident angle.
which affects the interparticle separation, the chain length, and, thereby, the optical properties. A shorter distance (stronger magnetic field strength) produces a longer “nano shutter” that facilitates the transmission of the light at 0°. When the orientation of the chains is perpendicular to the light beam path (Figure 4b), however, the difference in transmittance at different distances is very small. Furthermore, the duration of the magnetic fields also affects the assembly of the nanodiscs and, consequently, their optical properties. Even though the duration of the magnetic field is only half a minute, the optical transmittance is very different from that without a magnetic field (Figure 4c). The transmittance increased with the assembly time at 0°, and the increment in the transmittance was gradually reduced with an increased duration. This may be because the assembly is a dynamic process, and the chains (nano shutters) become longer as the assembly time increases. However, when the orientation of the chains was perpendicular to the light beam path (Figure 4d), the transmittance hardly changed with the assembly time. In short, the distance and the assembly time have a significant influence on the transmittance at 0° and little influence on the transmittance at 90°. In both the cases, the 1D chains became longer, and the number density of chains decreased accordingly in the colloidal dispersions as the assembly continued. Due to the parallel alignment of chains at 0°, the overall effective optical cross sections of the chains decreased, resulting in high transmittance in their colloidal dispersions at a longer duration. Under the condition of 90°, however, the effective optical cross sections of the chains were similar whether the chains were long or short due to the perpendicular alignment. Thereby, the transmittance of the colloidal dispersions showed negligible changes at different durations. The distinction in the optical properties of the nanodisc dispersions under different magnetic field directions can be easily observed by the naked eyes. At 0°, the colloidal dispersions of nanodiscs became transparent due to the high transmittance, so that the bird in the picture could be observed (Figure S5, Supporting Information). When switching the magnetic fields to a perpendicular orientation to the viewing directions, the nanodisc dispersions in cuvette quickly changed from transparent to opaque. This magnetic nanodisc system provides a pronounced contrast of optical transmittance between the “on” (0°) and “off” (90°) states and allows fast and reversible switching between transparent and opaque states (Video 4, Supporting Information).

The shape-dependent optical response of the magnetic colloidal dispersions can be utilized for designing novel advanced optical systems. Here, we demonstrate the dynamic tuning of the optical contrast by controlling the orientation of 1D colloidal assemblies of magnetic nanospheres and nanodiscs sealed in different capillary tubes. The nanodisc colloidal dispersion was near transparent when the magnetic fields were parallel to the incident light direction (0°). Therefore, the letters of “UCR” behind the capillary tubes could be observed. On the contrary, the nanosphere colloidal dispersion in the middle position was opaque with a brownish-yellow color. As a result, the letters behind the capillary tubes were completely invisible. When the direction of the magnetic field was perpendicular to the direction of the light, the “nano shutter” constructed from aligned 1D chains of nanodiscs will quickly “close” in time. The nanodisc colloidal dispersions on the left and right sides turned into black, and the letters of “UCR” disappeared. Instead, the windows made of the nanosphere chains were “open,” and the letters of “HUE” behind the capillary tubes could be seen. The contrast between the two samples is obvious, and under the control of the magnetic field, “UCR” and “HUE” signs can quickly switch between “appearance” and “disappearance” states (Video 5, Supporting Information). This magnetic assembly and alignment strategy can be used for preparing smart optical devices in many real-world applications. For example, the restroom signs can be reversibly and quickly switched by simply rotating the magnet by 90° each time (Figure 5c,d). As evidenced by Videos 6 and 7, Supporting Information, the optical switching in these colloidal dispersions was immediate without any noticeable delay. This fabrication approach is expected to be applied to other intelligent displays and switching systems, which can achieve fast and reversible tuning of the optical properties of devices in an efficient way due to the low energy consumption in manipulating magnetic fields.

The convenient assembly and orientation control of the 1D chains and their angle-dependent transmittance allow us to further design smart mechanochromic devices with optical transmission responsive to mechanical perturbation. As shown in the schematic of Figure 6a, a polymer film embedded with nanodisc chains was prepared by photopolymerization under a magnetic field. The angle between the orientation of 1D chains and the surface normal of the polymer film was adjusted to 45° by tuning the directions of the magnetic fields. The orientation of the nanochains in the polymer film can be adjusted by rotation, which affects the optical properties of the polymer film (Figure 6b).
When the rotation angle is 45°, the orientation of the nanochains will change to be perpendicular to the direction of the incident light. In contrast, when the rotation angle is −45°, the orientation of the nanochains is parallel to the direction of the incident light. Furthermore, the orientation of the nanochains in the polymer film is also responsive to inward bending and outward bending (Figure 6c). When the polymer was bent inward by 45°, the orientation of the nanochains in the left and right portions was parallel and perpendicular to the direction of the incident light, respectively. Conversely, when the polymer was bent outward by 45°, the oriented nanochains in the left and right portions became perpendicular and parallel to the incident light direction, respectively. Photographs of the polymer film with nanodisc chains at different rotation angles are shown in Figure 6d–f. When the rotation angle was 45° (Figure 6d), the polymer film was completely dark, and the information behind the film was invisible because the orientation of the nanodisc chains was perpendicular to the incident light direction. When the angle of rotation was 0°, it was still difficult to see the information behind the polymer film because the angle between the orientation of nanochains and the direction of the incident light was 45°, and the transmittance of light was still low. However, when the rotation angle was −45°, the orientation of the nanodisc chains was parallel to the incident light direction. Therefore, the “UCR” letters were clearly observed. When the polymer film was rotated from −45° to 45°, it was easy to switch between “transparent” and “opaque” states (Video 8, Supporting Information). In contrast to uniform transparency changes during rotation, bending induced different transparencies at the two ends of the film due to the differences between the orientations of 1D chains. When the polymer film was bent inward by 45°, the printed signal “2019” on the left side was observed due to the parallel alignment of the chains to the incident light direction (Figure 6g). For the right side of the film, however, it was completely dark, and the sign behind the film was blocked as the chains were perpendicular to the incident light direction. When the bending angle is 0°, the film was evenly dark, and the information behind the film was hardly observed. When the film was bent outward by 45°, the sign “2020” could be observed behind the right side of the films, whereas the sign behind the left disappeared. As discussed earlier, these optical properties of polymer films with nanodiscs are closely related to the orientation of nanodisc chains. The information encrypted behind the left and right sides of the film can be quickly switched using different bending angles (Video 9, Supporting Information). Through our ingenious design, we can assemble 1D nanochains with different optical properties. By combining two types of nanostructures (such as nanospheres and nanodiscs), fast and reversible switching between “appearance” and “disappearance” can be achieved. It is also possible to use only nanodiscs to realize the intelligent switching of the signals. This strategy provides a new idea for the design of fast and energy-saving intelligent displays and systems, and it is expected to achieve the dynamic regulation of intelligent systems through the orientational control of nanostructured magnetic components.

3. Conclusion

In summary, magnetic Fe₃O₄ nanostructures, including spheres, discs, and rods, are assembled into 1D chain-like structures by applying an external magnetic field. Our optical measurements under polarized and non-polarized light reveal that the optical transmittance is closely related to the structure and morphology of the building blocks. Contrary to the intuitive expectation, the
0D nanosphere and 1D nanorod dispersions exhibit low optical transmittance when the nanochains are parallel to the direction of the incident light. As the size of nanospheres (≈155 nm) is less than the half wavelength of visible light, the transmittance of the nanosphere chains is higher in the perpendicular case and lower in the parallel case, which is consistent with the theoretical predictions. The head-to-head assembly of nanorods due to magnetic anisotropy makes their optical response similar to that of nanospheres. However, as the lateral dimension (≈320 nm) of the Fe₃O₄ nanodiscs is larger than the half wavelength of most visible light, the transmittance of the assembled chains is the opposite of the nanosphere and nanorod chains. Specifically, Fe₃O₄ nanodisc chains exhibit excellent contrast between parallel and perpendicular directions due to their unique sheet structure anisotropy and “edge-to-edge” assembly. By fixing the 1D chains along a pre-designed direction in the photocurable polymer, we further propose a reliable strategy to prepare smart optical devices, whose optical transparency is responsive to mechanical perturbation in a precise and programmable manner. The oriented assembly of nanostructures with various shapes offers tunable optical transmittance that may find potential applications in designing many novel smart optical devices.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest
The authors declare no conflict of interest.

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