Supplementary Material (ESI) for Chemical Communications

SUPPORTING INFORMATION FOR

Double "Plug and Play" Templates Technology for Photo Controllable Drug Release Polyelectrolyte Multilayers

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Materials

Acryloyl chloride (AC), rhodamine B (RhB) and 3-aminopropyltriethoxysilane (APTES) were obtained from Shanghai Aladin Co., Ltd. (China) and used directly. 1-Azobiscyclo-hexanecarbonitrile (ABCN), N,N′-Dimethylformamide (DMF), 1,4-dioxane and Dimethyl sulfoxide (DMSO) were purchased from Aldrich. DMF was azeotropically distilled with benzene for dehydration and then distilled under vacuum. DMSO and 1,4-dioxane were previously dried with molecular sieves. ABCN was recrystallized from methanol before use. All other chemicals were used without further purification.

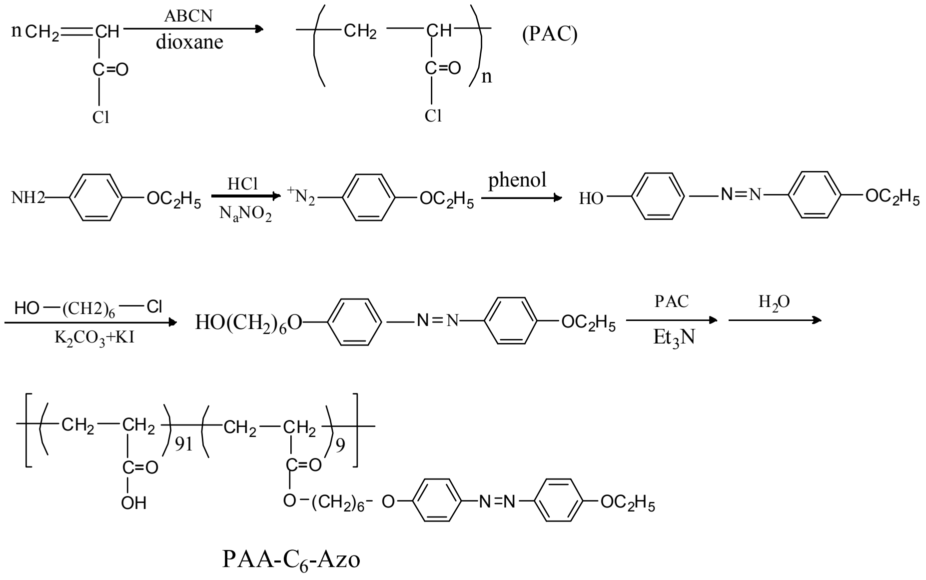
Preparation of Poly(acryloyl chloride) (PAC)

PAC was synthesized according to the literature.[1] Briefly talking, Acryloyl chloride (20 mL), dry 1,4-dioxane (20 mL), and ABCN (0.668 g) were added into a flask under N_2 protection. The flask was sealed and then heated in an oil bath (50 °C) for 14 h. The polymer was precipitated by adding petroleum ether (100 mL), collected by filtration, and washed twice with petroleum ether. The product was dried at 60 °C under vacuum for 48 h.

Preparation of PAA-C_6-Azo

PAA-C_6-Azo was prepared as described elsewhere.[2] PAC (0.3 g, 0.0033 mol), triethylamine

(0.56 mL, 0.0040 mol), and 2-[4-(4′-ethoxyphenylazo)phenoxy]ethanol (whose amount was determined by the required degree of functionalization) were dissolved in anhydrous DMF (33 mL). The mixture was stirred at room temperature for 12 h under N_2 protection. Then suitable amount of water was added into the mixture and stirred for 10 min. The product was precipitated from HCl water solution (0.01 mol/L), collected by filtration, washed several times with water, and dried under vacuum. The polymer was further purified by dissolving in THF and precipitated from petroleum ether, collected by filtration, and washed twice with petroleum ether. The final product was dried at 70 °C under vacuum for 24 h. The degree of modification was determined to be 9 mol% by 1H NMR.



Scheme S1 Synthesis route of PAA-C_6-Azo

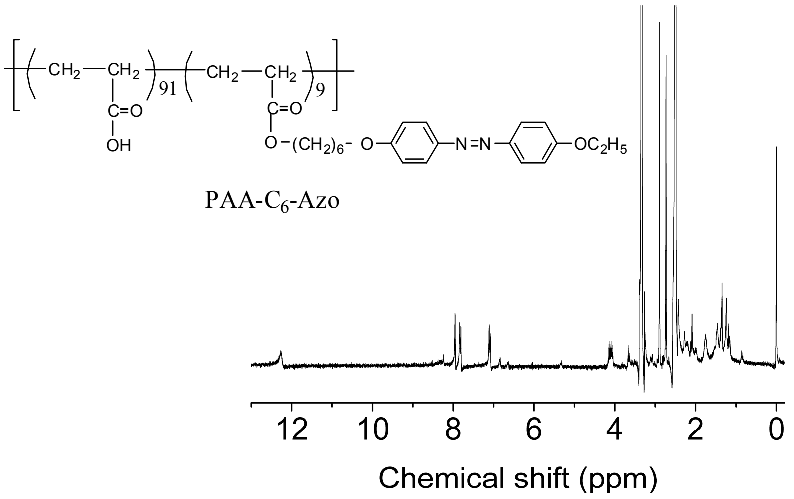
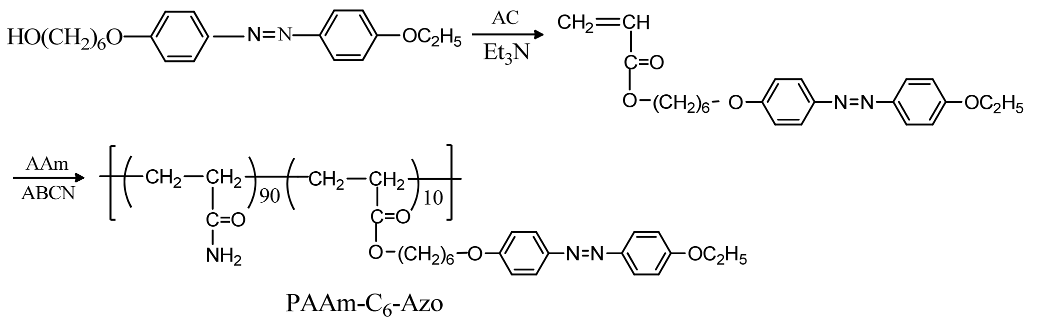


Fig. S1 The 1H NMR spectra of PAA-C_6-Azo

Preparation of PAA-C_6-Azo[3]

PAAm-C_6-Azo was prepared by radical copolymerization in DMF at 60 °C using ABCN (0.5 wt per cent with respect to the monomer) as a radical initiator. The degree of modification was determined to be 10 mol% by 1H NMR.



Scheme S2 Synthesis route of PAAm-C_6-Azo

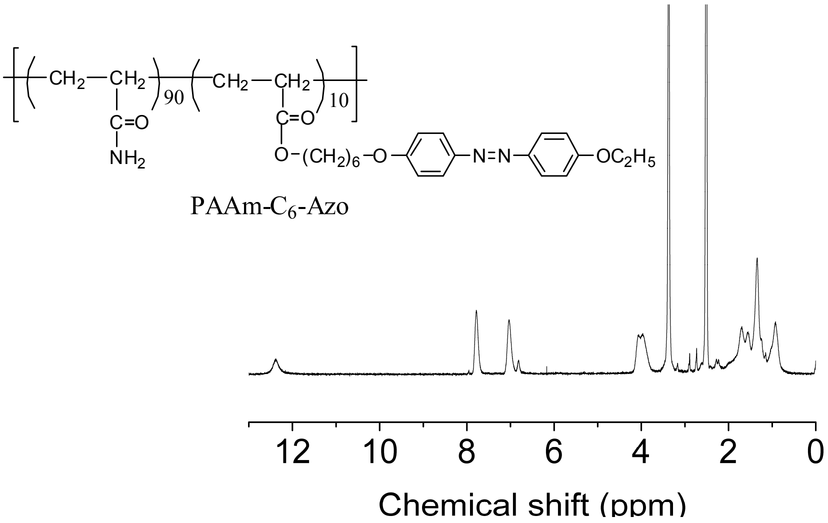


Fig. S2 The 1H NMR spectra of PAAm-C_6-Azo

Synthesis of α-CD-rhodamine B (α-CD-RhB)

α-CD-RhB was synthesized according to previous reports.[4]

Inclusion complex formation

The drug complexes of PAA-C_6-Azo/α-CD-RhB and PAAm-C_6-Azo/α-CD-RhB were prepared as follows: 32.2 mg (1.1×10^{-3} mmol) PAA-C_6-Azo and 29.6 mg (4.7×10^{-3} mmol) PAAm-C_6-Azo were respectively dissolved in 40 mL H_2O (a suitable amount of sodium hydrogen carbonate was added into the solution to promote the solubility of PAA-C_6-Azo). After completely

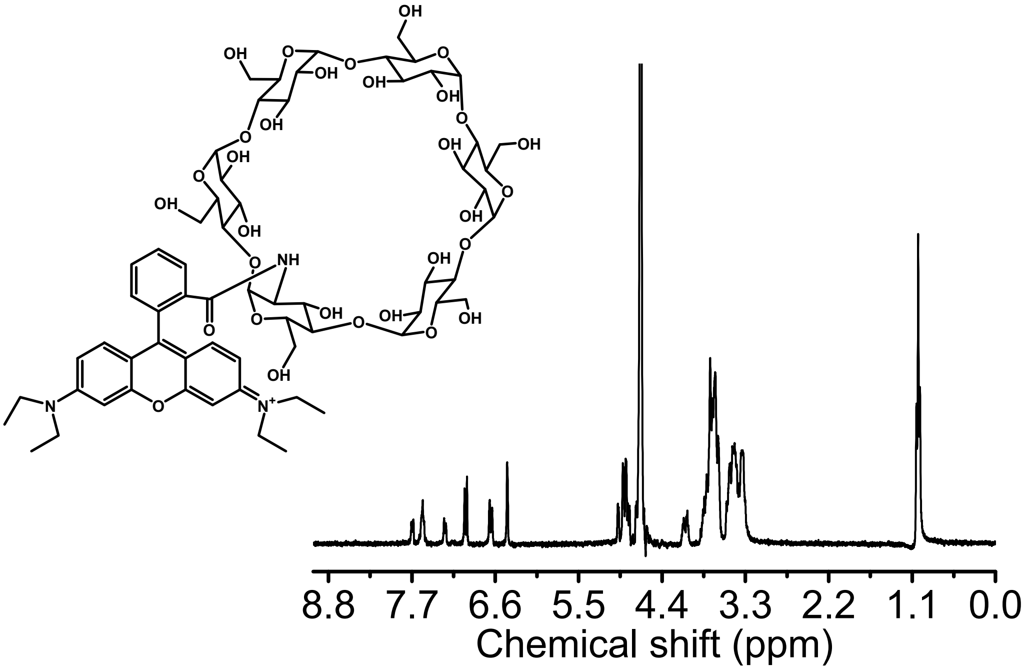


Fig. S3 The 1H NMR spectra of α-CD-RhB

dissolving, the pH values of the solution were adjusted to be 7.0 by adding a few drops of HCl dilute solution. Then 40 mg (0.0286 mmol) α-CD-RhB was respectively added under ultrasonic condition at room temperature. The mixtures were stirred overnight at room temperature and then dialysis against uncomplexed α-CD-RhB for 48 h in a dialysis tube.

Substrate preparation

Quartz slides were used as substrates for the UV-visible absorption, while CaF_2 plates were used for FT-IR measurements. A quartz substrate was immersed into a fresh piranha solution (30% H_2O_2/98% H_2SO_4, v/v =1:3; CAUTION: Piranha solution is a very aggressive, corrosive solution, and appropriate safety precautions should be utilized, including the use of acid-resistant gloves and adequate shielding) and heated until no bubbles were released. The substrate was rinsed carefully with deionized water and dried with nitrogen. The cleaned quartz slide was treated in 2% (v/v) APTES/95% ethanol solution for 20 min, and then was dehydrated at 110 °C for 1 h to obtain the amino-silanized quartz slide. For the FT-IR measurements, CaF_2 plates need to be modified with a precursor layer of poly(ethyleneimine) (PEI) before LbL deposition.

PAA-C_6-Azo/PAAm-C_6-Azo multilayer fabrication and characterization

32.2 mg (1.1 × 10^{-3} mmol) PAA-C_6-Azo and 29.6 mg (4.7 × 10^{-3} mmol) PAAm-C_6-Azo were respectively dissolved in 40 mL H_2O (a suitable amount of sodium hydrogen carbonate was added into the solution to promote the solubility of PAA-C_6-Azo). After completely dissolving, the pH values of the solution were adjusted to be 7.0 by adding a few drops of HCl dilute solution. A freshly treated quartz wafer or CaF_2 plate was alternately dipped in the PAA-C_6-Azo solution and the PAAm-C_6-Azo solution each for 10 mins. After each dipping, the wafer was washed with enough Milli-Q water for 2 mins. UV-vis spectra were measured using a Shimadzu UV-2550 spectrometer to monitor the fabrication of PAA-C_6-Azo/PAAm-C_6-Azo multilayer films as shown in Fig. S4. It can be seen that intensity of the absorbance of the multilayers increase with the number of dipping, which indicates the buildup of multilayers in a Layer-by-Layer manner. The multilayer exhibits the absorption bands between 300 and 370 nm, which is related to π-π* transition bands of the *trans*-azobenzene.

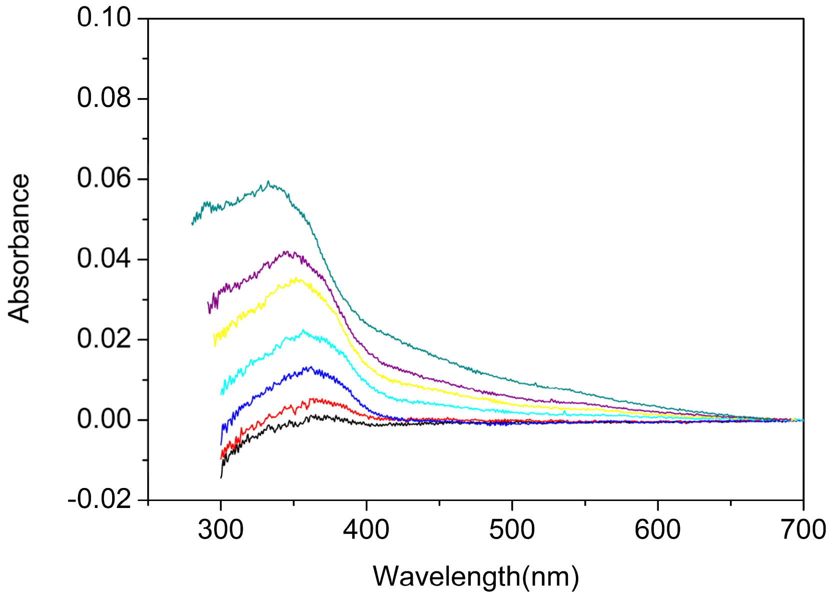


Fig. S4 UV-Vis absorption spectra of azobenzene films on a quartz wafer (from bottom to top: 1 to 7 monolayers)

FTIR measurements were made using a Bruker Tensor 27 FT-IR spectrometer to confirm the assembly process, as shown in Fig. S5. In a film of neat PAAm-C_6-Azo, the amide I peak (C=O stretching) and amide II peak (N-H mixed mode) appear at 1652 and 1609 cm^{-1}, respectively. The amide I peak is found to shift to higher frequency (1658 cm^{-1}) in the multilayer films due to the break of hydrogen bonding among the amide groups. It is well known that the C=O stretching absorption of carboxylic acids is observed at 1750 cm^{-1} in the monomeric state without hydrogen bonds and shifts to 1700 cm^{-1} for the dimeric structure with hydrogen bonds.[5] In the PAA-C$_6$-Azo film, the C=O stretching absorptions of -COOH and -COO$^-$ appear at 1706 and 1640 cm^{-1}, respectively. This indicates that most of the acid groups in PAA-C$_6$-Azo film are present in their nonionized form with dimeric structure. The C=O absorption of -COOH shifts to lower frequency (1704 cm^{-1}) in the multilayer films due to hydrogen bonding between the amide and acid groups. However, the peak intensity of –COOH is decreased and a strong -COO$^-$ peak is clearly seen at 1658 cm^{-1} (overlapping with the amide I peak). FTIR results above suggests only a low amount of the acid groups of PAA-C$_6$-Azo/PAAm-C$_6$-Azo LbL film are present in nonionized form , and electrostatic interactions between PAA-C$_6$-Azo and PAAm-C$_6$-Azo have been utilized as the main driving force of LbL assembly process.

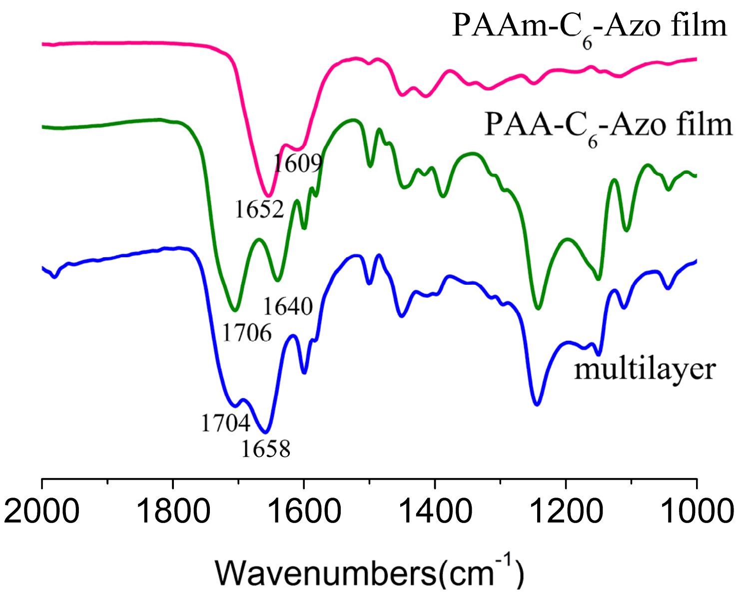


Fig. S5 FTIR spectra of layer-by-layer PAA-C$_6$-Azo/PAAm-C$_6$-Azo multilayer film on CaF$_2$ substrate, neat PAA-C$_6$-Azo film and PAAm-C$_6$-Azo film by flowing film-forming method.

Interestingly, PAA-C$_6$-Azo/PAAm-C$_6$-Azo multilayer showed good stability in water at a pH of about 7.0 or higher. A possible explanation could be that the azobenzene chromophores in multilayer tend to form aggregates which reinforce the stability of multilayers.[6] To test the above assumption, UV-vis spectra were measured to study the interactions between PAA-C_6-Azo and PAAm-C_6-Azo in water at a pH of 7.0 as shown in Fig. S6. After complexation between PAA-C_6-Azo and PAAm-C_6-Azo aqueous solution with 1:1 volume ratio, a single π-π* transition peak with significant shift and decline in intensity can be found as Fig. S6 (curve c). The blue shift in the absorption spectrum and the decline in intensity of absorption are characteristic features of producing H-aggregates in azobenzene system.[6] These results demonstrate that the stacking of azobenzene chromophores between double templates is attributed to the foramtion and stability of multilayer at high pH. This conclusion can be proved by the fact that multilayer also shows characteristic blue shift during the assembly deposition process (Fig. S4).

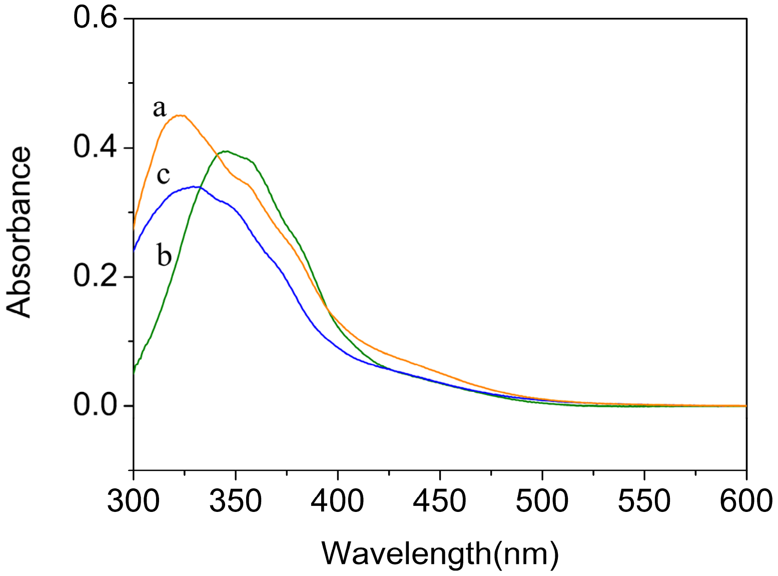


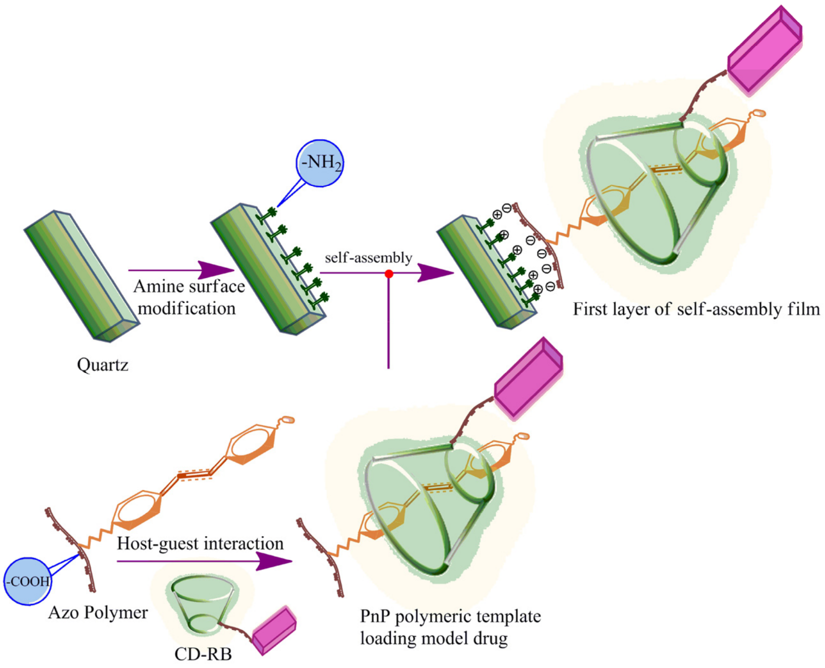
Fig. S6 Spectroscopic responses of PAA-C_6-Azo aqueous solution (1.8×10^{-5} mol/L) (a), PAA-C_6-Azo aqueous solution (1.8×10^{-5} mol/L) (b) and PAA-C_6-Azo/PAAm-C_6-Azo complex aqueous solution (1:1 volume ratio) (c).

PAA-C_6-Azo/PAAm-C_6-Azo multilayer loading α-CD-RhB fabrication

Schematic expression of the fabrication of the first layer of self-assemble film is shown in Scheme S3.

The extraction of α-CD-RhB from multilayers during the deposition process

Some groups have reported that the release of small molecules from the LbL film was related to the ionic strength of the solution during the assembly deposition process.[7] A similar experiment was adopted to understand the role played by salt in the extraction of α-CD-RhB, though the interaction between the polymer template and α-CD-RhB is different from that of LbL film mentioned above. We immersed a α-CD-RhB-loading multilayer of (PAA-C_6-Azo/PAAm-C_6-Azo)$_{12}$ (12 assemble monolayers) in a NaCl aqueous solution of different concentrations. As shown in Fig. S7, the extraction rate of α-CD-RhB from the multilayer film is indeed correlated with the concentration of NaCl solution.



Scheme S3 Schematic expression of the fabrication of the first layer of self-assemble film

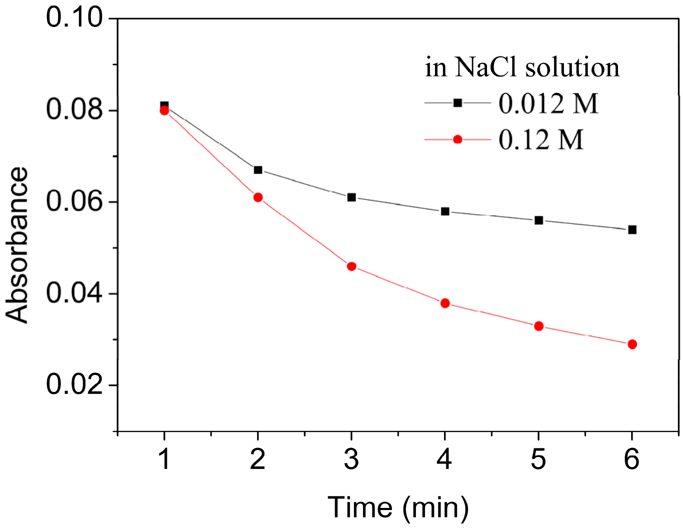


Fig. S7 Absorbance at 566 nm vs immersion time of (PAA-C_6-Azo/PAAm-C_6-Azo)$_{12}$ multilayer film in NaCl aqueous solution (0.012 M and 0.12 M).

The UV and vis light used

The UV irradiating light was from a high-intensity 365 nm UV lamp equipped with 5 in. diameter filter. The intensity of the lamp was 8000 μW/cm^2 at distance of 15 in. A 300 W xenon lamp equipped with a filter ($\lambda > 450$ nm) was used as visible light source. The sample was placed 15 cm away from the lamp. The surrounding temperature of the samples was controlled at 25 ^{o}C using a cold plate.

The reversibility of unloading/loading behavior

To examine the reversibility of unloading/loading behavior, a quartz substrate with 12 assemble monolayers was transferred into a 20.0 mL water and then irradiated by UV light. After 20 minutes of UV light irradiation, the sample was placed into a cuvette with 20.0 mL of α-CD-RhB aqueous solution (0.38 mM) and then irradiated by visible light for another 20 minutes. Monitoring of the unloading/loading curve of α-CD-RhB at $\lambda = 566$ nm is almost unchanged even after more than 8 cycles of the above steps, as shown in Fig. S8.

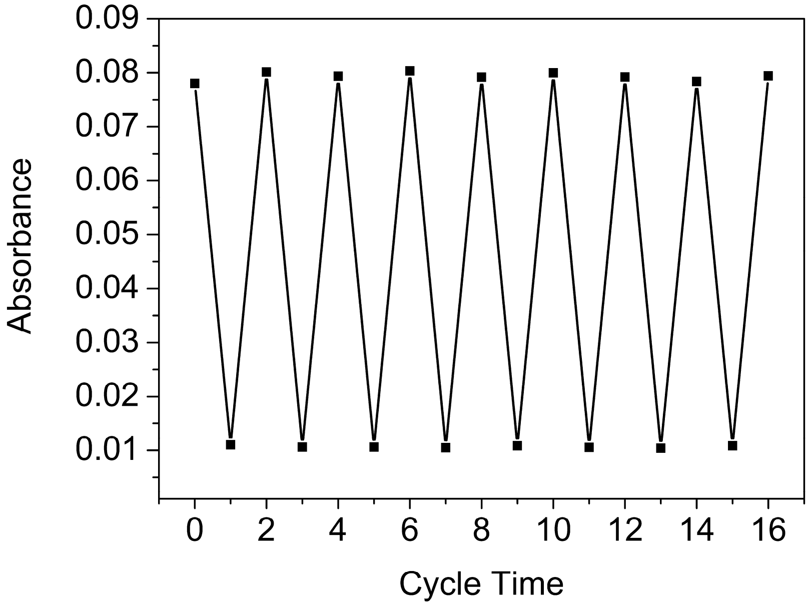


Fig. S8 The cyclic absorbance features of multilayer film at 366 nm as a result of the cyclic unloading and loading

The multilayers after 8 cycles of UV/visible light irradiation were viewed with confocal laser scanning microscopy (BD Laser at 543 nm). As shown in Fig. S9 (a), the reappearance of the red fluorescent surface confirm this reversibility after visible light irradiation. The multilayers after above treatment were also observed by TEM (Fig. S9 (b)).

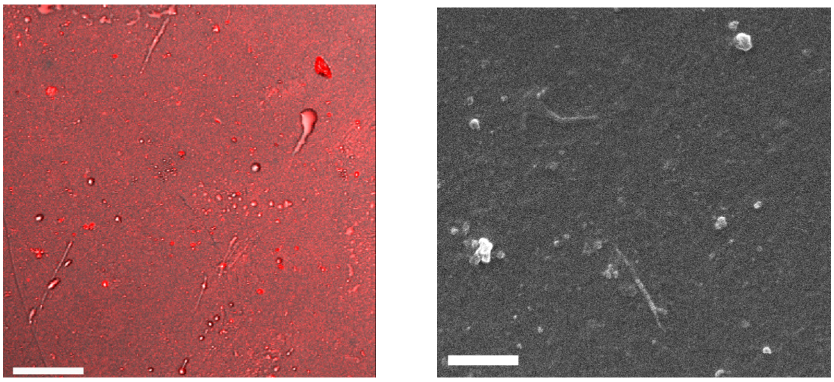


Fig. S9 a) Confocal microscopy image of multilayer films after 8 cycles of UV/visible light irradiation (the scale bar is 100 μm). b) SEM image of multilayer films after 8 cycles of UV/visible light irradiation (the scale bar is 2 μm).

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