**INTRODUCTION**

Organic ultralong room temperature phosphorescence (OURTP) materials with lifetimes over 0.1 s have been emerged as a hot research focus in recent years owing to their unique photophysical properties and innovative applications in many areas (1–8). Specially, OURTP materials have been increasingly regarded as promising alternatives for recording keys in security printing because of their multiplex properties of ultralong lifetime and tunable emission color that can render the printed information unable to be photocopied and cracked (9–12). Despite the huge advantages of OURTP materials in security printing, developing high-performance OURTP inks is still in the infancy on account of the intrinsic difficulties in simultaneously satisfying the requirements of ambient and amorphous afterglow emission, water solubility, full-color emitting, ultralong lifetime, and high phosphorescence quantum efficiency; all of them will lead to the bottlenecks of image quality and processability in security printing, leaving OURTP inks far from the rigorous requirements of commercial applications.

Current efforts in this field have been mainly focused on constructing various molecules and manipulating their lifetimes and quantum efficiency (13–15), while limited considerations have been devoted to developing water-soluble full-color OURTP emitters, let alone demonstrating their viable applications in multifarious security printing. To modulate the organic afterglow color, a variety of strategies have been proposed, including regulating material compositions and stacking motifs (16), using synergetic emission from molecular and aggregated phosphorescence (17, 18), as well as incorporating multiple emission centers (19, 20), and using triplet(T1)-singlet(S1) energy transfer (21, 22). Despite the flourishing advancements in OURTP materials showing color-tunable emission, there is still a daunting challenge to rationally realize water-soluble full-color OURTP materials with rational manipulation of afterglow colors, which are of great significance for environmental-friendly and multicolor security printing.

Förster resonance energy transfer (FRET) that transfers S1 and T1 excitons of donor (host) to the S1 of acceptor (guest) has been proved to be a concise approach to obtain full-color luminescent material systems (23–30). For instance, the delayed fluorescence with varied emission colors has been achieved by Kulla et al. (31) through coassembling energy donor of phosphors and energy acceptors of fluorescent dyes into a rigid matrix of poly(vinylalcohol); recently, they also achieved intense phosphorescence from fluorescent guest by anchoring heavy-atom substituted cationic molecule into inorganic silicate template (32). Moreover, Kirch et al. (33) observed a simultaneous and efficient dual-state FRET from both S1 and T1 states of a donor in a polymer matrix of poly(methyl methacrylate). Inspired by the tactful strategy in boosting full-color emission through FRET, we envision that implanting the T1-S1 phosphorescent FRET (P-FRET Fig. 1A) into host-guest material system could also be an effective strategy to effectively regulate afterglow color by adopting suitable OURTP matrix as energy donor and appropriate emissive guest as energy acceptor. To validate our hypothesis, by using a well-performance water-soluble amorphous polymer poly(acrylamide-co-N-vinylcarbazole) (PAMCz) with blue afterglow emission as host and a series of water-soluble and commercially available fluorescent emitters with different emissive colors ranging from green to red as guests, we designed and prepared the excellent water-soluble afterglow polymeric systems (Fig. 1B). Through facile regulation of the doping compositions and concentrations of guests, full-color organic afterglow was realized by on-demand modulation of the host-guest
organic afterglow system. Impressively, PAMCz host with the unprecedented OURTP lifetime of 4.2 s along with the successful P-FRET process facilitated by large spectral overlap between the phosphorescence spectrum of host and absorption spectrum of guest \(^{(34, 35)}\) renders the multicolor fluorescent guests with the state-of-the-art ultralong afterglow emission whose lifetimes are as high as 1.8, 1.5, 2.2, and 2.8 s for green, yellow, red, and white, respectively; these properties are among the best results of organic afterglow system \(^{(36, 37)}\). More notably, the developed water-soluble full-color ambient afterglow polymers can be expediently used as environmentally friendly OURTP inks in a red-green-blue (RGB) printing model to produce polychrome afterglow emission and applied to multicolor security printing. Benefiting from the flexibility in manipulating photophysical properties by P-FRET, this work not only provides an effective strategy to construct full-color afterglow emission but also establishes the new conceptual on-demand manipulation of afterglow colors for multicolor security printing.

**RESULTS**

**Synthesis and photophysical properties of PAMCz matrix**

PAMCz was synthesized by a binary radical copolymerization \(^{(38)}\) of vinyl carbazole (VCz) and acrylamide with a molar fed ratio of 1:100 (fig. S1) and characterized by \(^{1}\)H–nuclear magnetic resonance (NMR) and gel permeation chromatography (GPC) (figs. S2 and S3). Excellent water solubility of PAMCz with a solubility of 0.7 g/ml was observed. Owing to the intensive absorption effect of carbazole units and nonconjugation between carbazole groups and polyethylene main chain, PAMCz exhibits the representative absorption spectrum of carbazole with the maximum absorption peak at 290 nm (fig. S4). In addition, the amorphous thin film of PAMCz emits the ultraviolet (UV) fluorescence centered at 368 nm with a short lifetime of 13.5 ns (figs. S5 and S6 and tables S1 and S2), and the phosphorescence emission peaks at 414 nm can be observed under ambient conditions, indicating its strong OURTP feature. Amazingly, the lifetime of PAMCz phosphorescence is as high as 4.2 s, which is the best result among the reported afterglow polymers. It should be mentioned that the copolymerization is much better than the direct physical mixture of VCz or poly(vinyl carbazole) with polyacrylamide to realize ultralong lifetime of OURTP (fig. S7). Moreover, a high OURTP quantum efficiency of up to 10.0% was also observed for the PAMCz film under ambient conditions (table S3), suggesting its rather effective \(T_{1} \rightarrow S_{0}\) transition. The efficient afterglow property of PAMCz should be attributed to the strong spin-orbital coupling boosted by aromatic carbonyl groups and \(n-\pi^{*}\) transitions according to El-Sayed’s rule and efficient intermolecular interaction facilitated by a hydrogen-bonded network \(^{(39)}\). Excitingly, the broad blue afterglow emission ranging from 400 to 600 nm, ultralong lifetime, and consequent oscillator strength \(^{(33)}\) forebode PAMCz an ideal host for diversified fluorescent guests to construct full-color and highly efficient afterglow polymeric systems via P-FRET process.

**Energy transfer process**

To prove that using PAMCz as a host to construct full-color afterglow emission via P-FRET is feasible, we selected a water-soluble fluorescent dye of sodium fluorescein (Fluc) as a sensitized guest because...
its absorption spectrum (410 to 490 nm) is well overlapped with the afterglow emission spectrum of PAMCz (400 to 600 nm) (Fig. 1C), which is a prerequisite for a highly efficient P-FRET process. Experimentally, the photophysical properties of the Fluc/PAMCz films with the doping weight concentrations from 0.0 to 0.05 weight % (wt %) were systematically investigated to illustrate the detailed FRET process. As shown in Fig. 2A, the steady-state photoluminescence (PL) emission spectra of Fluc-doped PAMCz films display a gradual decrease of the PAMCz fluorescence emission at 368 nm (fig. S8) along with a sharp enhancement of Fluc fluorescence emission at a 550- to 650-nm region as the doping mass ratio of Fluc increases, which can be attributed to the occurrence of singlet-to-singlet FRET process from PAMCz to Fluc. As anticipated, the delayed PL spectra of Fluc/PAMCz-doped films show an extraordinary long-lived afterglow emission peaking at 560 nm with lifetimes over 1.7 s (Fig. 2, B to E, and table S1), confirming the presence of energy transfer process. Notably, with the doping concentration of the doped films increasing from 0.0 to 0.05 wt %, the visible afterglow color gradually changes from blue derived from PAMCz to yellow from Fluc (Fig. 2E), and the PAMCz afterglow emission is almost vanished at the doping ratio of 0.05 wt % with the greatly reduced lifetime from 4.2 to 2.0 s (Fig. 2D and fig. S9). In light of the large spectral overlap between the phosphorescence spectrum of PAMCz and absorption spectrum of Fluc as well as their effective dipole-dipole coupling, the non-radiative energy transfer from PAMCz to Fluc via P-FRET should be responsible for this ultralong afterglow emission peaking at 560 nm from Fluc/PAMCz-doped films. Quantitatively, the P-FRET radius was determined to be 30.3 Å (table S4), which is satisfied with the basic requirement of a typical FRET process with the energy transfer radii between 5 and 100 Å (34), confirming again the presence of P-FRET process between PAMCz donors and Fluc acceptors.

To further analyze the underlying mechanism of the energy transfer process in this polymeric system, we performed both nanosecond and femtosecond transient absorption (TA) investigations (figs. S10 and S11). Compared with the broad nanosecond TA band of pure PAMCz film peaked at 420 nm because of T_1-T_n transitions (fig. S10A),
a new TA band at ~550 nm emerges when 0.05 wt % Fluc was doped (fig. S10B). From the femtosecond TA band peaking at ~550 nm of Fluc in the absence of PAMCz (fig. S11), this new TA band should be related to the S0 of Fluc in PAMCz owing to the T1 to S0 P-FRET from the long-lived PAMCz to Fluc. This P-FRET was also verified by the largely reduced lifetime of TA peak at 420 nm (fig. S10, C and D) in the Fluc/PAMCz film. Notably, the P-FRET process is highly efficient with the phosphorescence energy transfer efficiency ($\Phi_{P\text{-FRET}}$) of up to ~72.2% (Fig. 2D and table S5) even at the extremely low doping concentration of 0.05 wt %. The time-resolved emission spectra of PAMCz and 0.05 wt % Fluc/PAMCz film excited at 299 nm further demonstrate the excellent stability of P-FRET process and afterglow emission over time (fig. S12). In addition, the almost disappeared afterglow emission of PAMCz in the 0.05 wt % Fluc/PAMCz-doped film means the nearly completed energy transfer from the host to the guest, suggesting that a fraction of radiative ET, besides FRET, should also be existing in the current highly efficient energy transfer process, and it can be further evidenced by the different quenching ratio of the emission peaks of PAMCz in Fluc/PAMCz-doped films (Fig. 2B).

To further gain deep understanding of this P-FRET process, we performed the excitation-phosphorescence emission mapping, lifetime, and phosphorescence quantum yield ($\Phi_p$) measurements. For the excitation-phosphorescence mappings, both of the pure PAMCz (0.00 wt % Fluc/PAMCz) film and 0.05 wt % Fluc/PAMCz-doped film exhibit almost the same excitation wavelength ranging from 208 to 362 nm (Fig. 2, F and G), while the bathochromic-shift excitation wavelength from 400 to 450 nm where Fluc has strong absorption (Fig. 1B) cannot excite the doped film to produce OURTP emission. These results testify again that the long-lived triplet excitons of PAMCz host are the only source to endow the fluorescent guest of Fluc with the ultralong afterglow characteristic via an efficient P-FRET process. Besides, the emission lifetime decay curves of PAMCz phosphorescence monitored at 414 nm (fig. S9 and table S1) show a gradual decrease of the lifetime from 4.2 to 3.1 s in 0.01 wt % Fluc/PAMCz film, which further reduces to 2.9 s for 0.03 wt % Fluc/PAMCz film. At the same time, the decay profiles of Fluc monitored at main emission bands exhibit the afterglow characteristic with the lifetimes spanning from 1.7 to 3.1 s (table S1). Owing to the excellent fluorescent properties of Fluc, the PL quantum yields (PLQYs) ($\Phi_{SPFL}$) increase constantly with the doping ratio running high for these films (Fig. 2D and table S2). Although no amplification effect of Fluc’s emission through the FRET process was observed (fig. S13 and table S6), the 72.2% $\Phi_{P\text{-FRET}}$ of the 0.05 wt % doped film results in a substantially enhanced $\Phi_{SPFL}$ of 30.5%, nearly 1.5-fold higher than that of the pure PAMCz film (20.7%). These results indicate that P-FRET strategy is not only an effective way to modulate the afterglow color but also an alternative avenue to improve the phosphorescence quantum yield.

**Mechanism and feasibility confirmation of the P-FRET for full-color afterglow**

By means of systematically experimental understandings of photophysical properties of Fluc-doped PAMCz film at different weight concentrations, a reasonable mechanism for FRET processes can be proposed: Part of the photoexcited singlet excitons ($S_1^H$) in the host matrix directly transfer to the singlet excited state of guest ($S_1^G$) through an $S_1^H \rightarrow S_1^G$ FRET process, thus gifting the efficient fluorescence emission through radiative decay from the $S_1^G$ to the ground state; meanwhile, the other part of photoexcited $S_1^H$ is readily transferred to long-lived triplet excitons of host ($T_1^H$) via intersystem crossing and then constantly transferred to the $S_1^G$ through a $T_1^H \rightarrow S_1^G$ P-FRET process, resulting in the afterglow emission from the radiative decay of $S_1^G$ excitons to the ground state (Fig. 3A). Moreover, radiative ET due to reabsorption also works here for the efficient energy transfer in sensitizing the afterglow emission of the fluorescent emitters.

On the basis of this mechanism, we reason that the afterglow color can be continuously varied by simply and appropriately selecting the fluorescence guests with different $S_1^G$ energy levels. As illustrated in Fig. 1B, the phosphorescence (delayed time, 10 ms) spectrum of PAMCz ($\lambda_{phos} = 400$ to 600 nm) exhibits the favorable spectra overlaps with the absorption spectra of green fluorescence emitter of sodium 3,9-perylene dicarboxylate (PDB) ($\lambda_{abs} = 400$ to 470 nm), yellow fluorescence emitter of rhodamine 123 (Rh123) ($\lambda_{abs} = 450$ to 530 nm), and red fluorescence emitter of rhodamine B (RhB) ($\lambda_{abs} = 480$ to 570 nm), which meets the basic prerequisite for a P-FRET process. As anticipated, the green, yellow, and red afterglow emissions could be successfully achieved from PDB-, Rh123-, and RhB-doped PAMCz polymeric systems, respectively (Fig. 3B), affording a simple but effective method to construct color-tunable OURTP material systems. Similar to the Fluc/PAMCz hybrid film, the visible afterglow emissions after removing the UV-excitation source for PDB/PAMCz, Rh123/PAMCz, and RhB/PAMCz films also demonstrate the presence of efficient P-FRET process (Fig. 3, B to K). To further seek the optimal doping ratios for preferable energy transfer from PAMCz to fluorescent guest, the OURTP emission of these host-guest doped films at different concentrations was monitored; the optimally doped concentrations for PDB/PAMCz and Rh123/PAMCz-doped films are 1.0 and 0.1 wt % (Fig. 3, C and D, and figs. S14 to S17); particularly, for the RhB/PAMCz film, the delayed PL spectra of PAMCz gradually decline as the doped concentrations increase from 0.1 to 1.0 wt % and then remain unchanged when the concentrations increase from 1.0 to 2.0 wt %, suggesting that 1.0 wt % is the optimal doping concentration, which is also proved by their almost unchanged afterglow lifetimes (Fig. 3E and figs. S18 and S19) (40). Expectantly, excitation-phosphorescence emission mappings of the optimal weight concentration fluorescent molecule–doped PAMCz films also indicate that these excellent afterglow emissions from the corresponding fluorescent guests should be attributed to the efficient P-FRET from PAMCz to the fluorescent guests because they demonstrate almost the identical excitation wavelength ranging from 208 to 362 nm to that of the host of PAMCz (Fig. 3, F to H). Moreover, the time-resolved emission spectra also show that the P-FRET process and afterglow emission are quite stable over time (figs. S20 to S22). Notably, with the help of the impressive OURTP lifetime of PAMCz host and the successful P-FRET process, the 1.0 wt % PDB/PAMCz-, 0.1 wt % Rh123/PAMCz-, and 1.0 wt % RhB/PAMCz-doped films exhibit the remarkable lifetimes of 1.8, 1.5, and 2.2 s (figs. S23 to S25 and table S1), one of the best results for green, yellow, and red afterglow, respectively.

**Schematization of on-demand modulating afterglow color**

With the merits of preparation controllability and modulation flexibility, these host-guest polymeric systems are encouraging candidates that can prepare high-performance OURTP materials with on-demand modulated afterglow color. As a proof of concept, we outlined the color palettes (Fig. 4A) through simply varying the appropriate fluorescent guests and setting the corresponding doped concentrations.
in the host-guest polymeric systems. The color palette is quite sensitive to doped guests and concentration as manifested by different afterglow emissions of the resulting polymeric systems, resulting in a broad range of afterglow emission colors from blue to red. Experimentally, the multicolor afterglow of cyan, yellow, and magenta can be facilely enabled through doping 0.1 wt % PDB, 0.1 wt % Rh123, and 0.5 wt % RhB into PAMCz host, respectively (Fig. 4, B to E). On the basis of this P-FRET strategy, not unexpectedly, the bright white-light afterglow emission can be easily achieved when regulating the doping weight concentration of Rh123/PAMCz to 0.04 wt % (Fig. 4F and fig. S26). The Commission Internationale de l’Eclairage (CIE) coordinate of the white afterglow is located at (0.34, 0.34), fully closed
Nevertheless, because the duration of blue afterglow emission is longer than that of yellow afterglow emission, the time-resolved emission spectra of 0.04 wt % Rh123/PAMCz illustrate that the afterglow color gradually turns from white light to blue with elongating delayed time (fig. S27). Furthermore, a multistage FRET was also realized in a three-component RhB-doped 1.0 wt % PDB/PAMCz films, showing different lifetimes and afterglow emission colors through tuning the doping concentrations (fig. S28). This developed multicolor afterglow from cyan to red via effective P-FRET, along with the blue OURTP emission from PAMCz host, allows the current afterglow polymer systems to serve as full-color OURTP inks for multicolor security printing. The ability to on-demand manipulate the afterglow color in a user-controlled and modular manner remarkably upgrades the encryption attributes of security printing boosted by the inherently new OURTP inks.

**Demonstration of the multicolor security printing via RGB model**

In light of the full-range and flexible adjustability of afterglow color for the developed amorphous polymeric systems (fig. S29), they are especially applicable to time-resolved multicolor security printing in RGB model with blue, green, and red channels (Fig. 5A). The RGB model is well compatible with commercially available ink-jet printing technology; by directly loading RGB OURTP inks of 2.0 wt % RhB/PAMCz (R), 0.05 wt % Fluc/PAMCz (G), and PAMCz (B) into ink cartridges, diversified security patterns can be expediently printed. To illustrate the potential applications of the RGB model in security printing, monochrome quick response (QR) and bar codes (Fig. 5B) that are virtually invisible under natural light were directly printed using OURTP ink from the blue channel containing PAMCz aqueous solution. No patterns can be identified under UV excitation because of the interference of blue background fluorescence from the printing paper, while the blue afterglow images are clearly revealed when the UV light is removed. In addition, we further printed the encrypted roses showing RGB afterglow emission to demonstrate the feasibility of security printing. As shown in Fig. 5C (top), only the false pattern of roses showing green and red fluorescence could be observed on the parchment, and the leaves with blue fluorescence are indiscernible because of the blue background fluorescence interference of parchment under 254-nm UV-light excitation; after turning off the 254-nm UV light, the blue afterglow leaves appear, and the true pattern of integrated roses with RGB emission from cyan to red still stand out. Moreover, as the regulable OURTP inks derived from the RGB model exhibit different afterglow color and lifetime, the multiplexing encryption is successfully obtained; the afterglow of “NJUPT” letters printed by disparate OURTP color combinations disappeared at different times because of their different lifetimes spanning from 0.7 to 2.4 s (fig. S32 and table S7); for example, the letter “N” with red afterglow emission and lifetime of 0.7 s is blurred after 3 s, but the blue “T” printed by PAMCz ink can still be recognized after 7 s as its ultralong lifetime of 2.4 s. The above results convincingly demonstrate that these polymeric OURTP inks have great potential applications in multicolor security printing.

**DISCUSSION**

In summary, we have succeeded in proposing an efficient approach to develop full-color organic afterglow materials with on-demand modulation in a water-soluble host-guest polymeric system.
The principle of this strategy leans upon large spectral overlap between the phosphorescence spectrum of host and absorption spectrum of guest for activating an efficient P-FRET process. With inherent preparation controllability and modulation flexibility of the developed polymeric systems, a possibly tremendous library of varied afterglow color combinations ranging from blue to red and even white with the unprecedented lifetimes up to 4.2 s and high PL yield of 36% can be successfully generated via simply varying the appropriate fluorescent guests and setting the corresponding doped concentrations into a blue afterglow polymer matrix under ambient conditions. Furthermore, the polymeric afterglow systems can be applied as security inks with built-in multiplexing lifetime and color-tunable encryption, thus enabling multicolor information encryption with RGB printing technology. This study not only paves a straightforward way to develop full-color afterglow materials by phosphorescence sensitization strategy but also offers an insightful guideline on producing multicolor OURTP inks through on-demand engineering the afterglow color in a user-controlled and modular manner for multiplex security printing.

**MATERIALS AND METHODS**

**Materials**

All the materials and solvents in the experiments were used without further purification unless other mentioned. Manipulations involving air-sensitive reagents were performed in an atmosphere of dry argon. Fluc, PDB, Rh123, RhB, VCz, acrylamide, and azodiisobutyronitrile (AIBN) were purchased from Sigma-Aldrich, Acros, or Alfa Aesar. Tetrahydrofuran (THF) was dried and purified by routine procedures.

**Measurements**

$^{1}$H- and $^{13}$C-NMR spectra were recorded on Bruker Ultra Shield Plus 400 MHz instruments with D$_2$O as the solvents and tetramethylsilane as the internal standard. Aqueous gel GPC was performed on Viscotek TDA305 max, using 0.1 M NaNO$_3$ solution as the mobile phase at the flow rate of 0.7 ml min$^{-1}$. Powder x-ray diffraction patterns were measured using a Bruker D8 Advance diffractometer (Cu Ka: $\lambda = 1.5418$ Å) under ambient conditions. UV-visible, fluorescence, and phosphorescence spectra were recorded on a Jasco V-750 spectrophotometer and Edinburgh FLS980. Phosphorescence spectra were obtained using an Edinburgh FLS980 fluorescence spectrophotometer at 298 K with a 10-ms delay time after excitation using a microsecond flash lamp. The absolute PLQY was obtained using an Edinburgh FLS980 fluorescence spectrophotometer equipped with an integrating sphere, and the wavelength-dependent sensitivity of the detector has been calibrated automatically by Edinburgh Instruments during PLQY measurement. For fluorescence decay measurements, picosecond pulsed light-emitting diode (EPLED-295; wavelength, 295 nm and pulse width, 833.7 ps) was used. The microsecond flash lamp produces short, typically a few microseconds, and the high-irradiance optical pulses for phosphorescence decay measurements in the range from microseconds to seconds. The kinetic measurements, afterglow spectra, and ultralong lifetimes were also measured.
using an Edinburgh FLS980 fluorescence spectrophotometer. Excitation-phosphorescence mapping was measured using Hitachi F-4700 with a 25-ms delay time under ambient conditions. Nano-second time-resolved transient difference absorption spectra were recorded on an Edinburgh LP920 laser flash photolysis spectrometer. TA spectroscopy was performed using a commercial femtosecond pump-probe system (Transipent Absorption Spectrometer, Newport Corporation). The multiexponential photoluminescent decays [I(t)] of PAMCz and acceptor-doped PAMCz films were described using the following equation

\[ I(t) = \sum B_i e^{-t/\tau_i} \]  

where \( B_i \) and \( \tau_i \) represent the amplitudes and lifetimes of the individual components for multiexponential decay profiles, respectively.

The average lifetime was calculated by the function of

\[ \tau_{ave} = \sum \varphi_i \tau_i \]  

where \( \varphi_i \) is the amplitude fraction.

To get the intensity-averaged lifetime (\( \tau_{int} \)), the \( \varphi_i^{\text{int}} \) is defined by the function of

\[ \varphi_i^{\text{int}} = \frac{B_i \tau_i}{\sum B_i \tau_i} \times 100\% \]  

\( \tau_{int} \) is achieved by the function of

\[ \tau_{int} = \sum \varphi_i^{\text{int}} \tau_i \]  

To get the amplitude averaged lifetime (\( \tau_{amp} \)), which was used for the analyses of FRET process, the \( \varphi_i^{\text{amp}} \) is defined by the function of

\[ \varphi_i^{\text{amp}} = \frac{B_i \tau_i}{\sum B_i \tau_i} \times 100\% \]  

\( \tau_{amp} \) is achieved by the function of

\[ \tau_{amp} = \sum \varphi_i^{\text{amp}} \tau_i \]  

Synthesis of PAMCz

PAMCz was synthesized via isothermal precipitation polymerization. Briefly, into a 250-ml two-necked round-bottom flask was placed N-vinylcarbazole [96.5 mg, 0.5 mmol, 1.00 equivalent (eq.)], acrylamide (3.55 g, 50.0 mmol, 100 eq.), and AIBN (83.0 mg, 0.505 mmol, 1.01 eq.). Then, the fresh distilled THF (25 ml) was injected into the flask, and the mixture was stirred at 55°C for 12 hours under an argon atmosphere, during which the white solid was constantly precipitated out from the solution. Afterward, the reaction mixture was cooled to room temperature, and the precipitate was collected through filtration, followed by washing with dichloromethane, acetone, and petroleum ether in sequence. Then, the solid was dissolved in de-ionized water and dialyzed by a dialysis tube (molecular weight cutoff = 1000) for 72 hours. Last, the product was dried to yield white solids in 87.3% yield. \( M_w = 13,349; M_m = 33,693; \) polydispersity index = 2.52 as measured by aqueous GPC.

General procedures for the preparation of fluorescent guest-doped polymeric film

First, PAMCz and the appropriate amount of fluorescent guest were dissolved in 15 ml of deionized water, followed by the sonication for 10 min under ambient conditions. Subsequently, the mixture was vigorously stirred at 60°C for 1 hour to obtain the transparent solution. Last, the well-mixed solution was poured into a clean petri dish and dried at 70°C in an oven to prepare the amorphous polymeric film.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at https://science.org/doi/10.1126/sciadv.abk2925

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