

Synthesis and Self-Assembly of Dynamic Covalent Block Copolymers: Towards a General Route to Pore-Functionalized Membranes

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General Methods and Materials

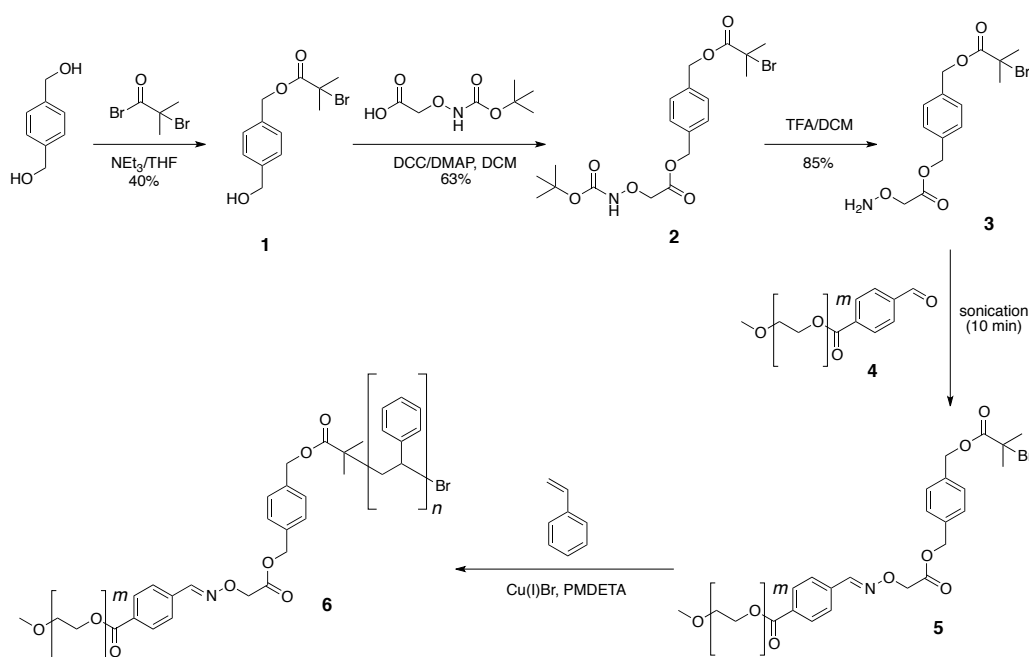
4-carboxybenzaldehyde, polyethylene glycol monomethyl ether ($M_n = 5000$), 1-ethyl-3-(3-dimethylaminopropyl)carbodiimide hydrochloride (EDCI.HCl), 1-hydroxybenzotriazole (HOBt), 4-dimethylaminopyridine (DMAP), p-xylene glycol, 2-bromoisobutyryl bromide, 2-(tert-butyloxycarbonylaminoxy)acetic acid, *N,N'*-dicyclohexylcarbodiimide (DCC), styrene, Cu(I)Br and pentamethyldiethylenetriamine (PMDETA) were purchased from commercial sources. NMR spectra were recorded on a Bruker AV300 MHz and AV500 MHz spectrometers, using CDCl₃ as the solvent. Mass spectrometry analyses were performed using an electron ionization (EI) MS spectrometer (Micromass AutoSpec-Ultima). MALDI-TOF mass spectra (matrix: DCTB) were recorded on a Bruker UltraFlex II MALDI-TOF mass spectrometer. Analytical GPC measurements were performed using a Viscotek GPC system

equipped with a pump and a degasser (GPCmax VE2001, flow rate 1.0 mL/min), a detector module (Viscotek 302 TDA) and three columns (2×PLGel Mix-C and 1×ViscoGEL GMHHRN 18055, 7.5 × 300 mm for each) using chloroform as an eluent. IR spectra were recorded using a Bruker Tensor 27 ATR-FT-IR spectrometer (Bruker Optic GmbH, Vienna, Austria). Top-view microstructures of the thin films were characterized using scanning electron microscopy (FEG-SEM, Zeiss LEO Gemini 1530, Germany) with an in-lens detector. Prior to imaging, the thin films were coated with platinum in order to avoid charging and to allow imaging at higher resolutions. Further morphological and structural characterization was carried out by transmission electron microscope (TEM) (Philips, CM 12) operating at an accelerating voltage of 100 kV. The tapping mode AFM images were taken using a multimode microscope with a NanoScope IIIa Controller (Nanoscope IIIa, Veeco, USA). Fluorescent dye functionalized thin films were observed using a fluorescence microscope AX10Imager M1m (Zeiss, Germany). Images were taken with a low light-intensity CCD camera (PentaMax 12 bit CCD; Princeton Instrument Inc., Trenton, NJ). Zeiss filter set No. 49 was used under mode-I and Zeiss filter set No. 15 was used under mode-II. The UV/Vis measurements were carried out on a Lambda 20 double beam UV/Vis-spectrophotometer from Perkin-Elmer.

Thin film studies: 1 wt% toluene solution of the diblock copolymer, **4**, was spin coated on a silicon wafer and the resulting thin film was placed in a glass petri dish with two holes on the lid and a water circulation circuit around the container. Two small containers with wide openings, containing benzene (~5 mL) and water (~2 mL), were placed inside the petri dish and the whole system was cooled to 15 °C. The cooled petri dish was then placed in a teflon chamber with controlled humidity (>90%). This way the annealing was carried out for a period of 3 days. During this period, the benzene container was refilled three times via a syringe. After this, the petri dish lid was removed and the film was exposed to high humidity conditions for few minutes before removal from the teflon chamber. After annealing, the thin films was transferred to a TFA bath set at 50 °C for 3 days (Alternatively, 6 days at room temperature produced similar results). Once removed from TFA bath, the films were quickly washed thoroughly with DMSO and ethanol and then immediately put into a water bath for 3h. After this treatment the films floated on the water surface and were gently transferred onto a TEM grid.

Postfunctionalization reactions: After TFA treatment, the films were washed with water after some time-delay. This was important in keeping the films attached to the substrate. These samples were immersed in DMSO (EtOH for fluorescein) in the presence of the respective dye molecule for 18 hours. The films were then washed extensively with DMSO and EtOH to remove any physically absorbed dye molecules. For functionalization with gold, similar films attached to the substrate were used in conjunction with the procedure described in reference 4b of the main manuscript. In this case, HF bath was used to detach the film from silicon substrate and to transfer the film to the TEM grid.

Synthesis



Scheme 1. Synthesis of the imine-linked PEG-*b*-PS dynamic block copolymer.

Compound 1: Hydroxy-functionalized ATRP initiator, **1**, was synthesized following the literature procedure.¹ ¹H-NMR (δ , ppm, 300 MHz, CDCl₃): 1.95 (s, 6H, (CH₃)₂Br), 4.70 (s, 2H, ArCH₂OH), 5.20 (s, 2H, CH₂ArCH₂OH), 7.38 (s, 4H, Ar); ¹³C-NMR (δ , ppm, 75 MHz, CDCl₃): 31.0, 55.9, 65.0, 67.3, 127.4, 128.4, 134.9, 141.4, 171.8; ESI-MS: m/z = 304.05 [M+NH₄]⁺ (calcd. 286.02 for C₁₂H₁₅BrO₃); Elemental analysis (%) calcd: C: 50.19, H: 5.26, O: 16.72, Br: 27.83; found: C: 50.13, H: 5.29, O: 16.9, Br: 27.73.

Compound 2: Hydroxy-functionalized ATRP initiator **1** (1.0 g, 3.5 mmol), 2-(tert-butyloxycarbonylamino)acetic acid (0.8 g, 1.2 mmol), DCC (1.07 g, 5.1 mmol) and DMAP (0.063 g, 0.5 mmol) were taken in 15 mL of DCM and CH₃CN mixture (in 2:1 *v/v*)

and the resulting reaction mixture was stirred at 25 °C for 20 h. After the reaction was complete, solvents were removed under reduced pressure and the crude solid was dissolved into minimum amount of DCM and then filtered. The filtrate was concentrated and purified by column chromatography (heptane/ethyl acetate; 9:1) to yield 1.0 g of compound **2** (Yield = 63%). ¹H-NMR (δ, ppm, 300 MHz, CDCl₃): 1.46 (s, 9H, (CH₃)₃), 1.95 (s, 6H, (CH₃)₂Br), 4.48 (s, 2H, NHOCH₂), 5.21 (s, 4H, CH₂ArCH₂), 7.38 (s, 4H, Ar), 7.74 (s, 1H, NH); ¹³C-NMR (δ, ppm, 75 MHz, CDCl₃): 28.4, 31.0, 55.9, 66.8, 67.4, 72.8, 82.4, 128.4, 128.9, 135.4, 136.2, 156.5, 169.7, 171.7; ESI-MS: *m/z* = 477.12 [M+NH₄]⁺ (calcd. 459.09 for C₁₉H₂₆BrNO₇); Elemental analysis (%) calcd: C: 49.58, H: 5.66, N: 3.04, O: 24.33, Br: 17.36; found: C: 49.28, H: 5.67, N: 3.08, O: 24.23, Br: 17.06.

Oxy-imine, 3: To a solution of compound **2** (0.8 g, 1.7 mmol) in dry DCM (10 mL), TFA (10 mL) was added and stirred for 12 h at 25 °C. After the reaction was over, aqueous solution of NaHCO₃ was added to it and stirred for 30 min, then the reaction mixture was extracted with DCM, dried over MgSO₄ and removed the solvent to obtain 0.53 g of compound **3** (Yield = 85%). ¹H-NMR (δ, ppm, 300 MHz, CDCl₃): 1.95 (s, 6H, (CH₃)₂Br), 4.29 (s, 2H, CH₂ONH₂), 5.21 (s, 4H, CH₂ArCH₂), 7.38 (s, 4H, Ar), ¹³C-NMR (δ, ppm, 75 MHz, CDCl₃): 31.0, 55.9, 66.3, 67.5, 70.3, 128.4, 128.7, 135.8, 136.1, 170.6, 171.8; ESI-MS: *m/z* = 360.04 [M+H]⁺ (calcd. 359.04 for C₁₄H₁₈BrNO₅); Elemental analysis (%) calcd: C: 46.68, H: 5.04, N: 3.89, O: 22.21, Br: 22.18; found: C: 46.58, H: 5.07, N: 3.76, O: 22.16, Br: 22.20.

PEG Aldehyde, 4: To a solution of polyethylene glycol monomethyl ether (*M_n* = 5000) (5.0 g, 1.0 mmol) in 15 mL of pyridine, 4-carboxybenzaldehyde (0.195 g, 1.3 mmol), EDCI.HCl (0.411 g, 2.0 mmol), HOBT (0.270 g, 2.0 mmol) and DMAP (0.037 g, 0.3 mmol) were added and the resulting reaction mixture was stirred at 50 °C for 72 h. Pyridine was removed under reduced pressure and the crude solid was dissolved into minimum amount of DCM and then precipitated into 200 mL of diethyl ether. The precipitate was filtered and the solid was purified by column chromatography (DCM/MeOH; 9.5:0.5) to yield 4.7 g of **1** (Yield = 91%). ¹H-NMR (δ, ppm, 300 MHz, CDCl₃): 3.35-3.45 (m, CH₃(OCH₂CH₂)_nOCH₂CH₂OCOArCHO), 3.51-3.77 (br m, CH₃(OCH₂CH₂)_nOCH₂CH₂OCOArCHO), 3.81-3.93 (m, CH₃(OCH₂CH₂)_nOCH₂CH₂OCOArCHO), 4.48 (t, 2H, CH₃(OCH₂CH₂)_nOCH₂CH₂OCOArCHO), 7.91 (d, *J* = 8.1 Hz, 2H, Ar), 8.18 (d, *J* = 9.0 Hz, 2H, Ar), 10.13 (s, 1H, CHO); ¹³C-NMR (δ, ppm, 125 MHz, CDCl₃): 64.8, 68.7-72.7, 129.8, 129.9, 135.2, 139.3, 165.7, 191.8; GPC (CHCl₃): *M_n* = 5500, *M_w* = 5600, PDI (*M_w*/*M_n*) = 1.02.

PEG macroinitiator, 5: Oxy-imine **3** (2.0 g, 0.389 mmol) and PEG aldehyde **4** (0.14 g, 0.389 mmol) were taken together in 10 mL of chloroform and sonicated for 10 min. Then chloroform was removed under reduced pressure and the solid was washed with diethyl ether (2×10 mL) to yield 2.1 g of PEG macro-initiator, **5**, (Yield = 98%). ¹H-NMR (δ, ppm, 300 MHz, CDCl₃): 1.95 (s, 6H, (CH₃)₂Br), 3.35-3.45 (m, CH₃(OCH₂CH₂)_nOCH₂CH₂OCOArCHO), 3.51-3.77 (br m, CH₃(OCH₂CH₂)_nOCH₂CH₂OCOArCHO), 3.81-3.93 (m, CH₃(OCH₂CH₂)_nOCH₂CH₂OCOArCHO), 4.48 (t, *J* = 4.8 Hz, ArCOOCH₂), 4.79 (s, 2H, CH₂ON=CH), 5.20 (d, *J* = 9.0 Hz, 4H, CH₂ArCH₂), 7.37 (s, 4H, CH₂ArCH₂), 7.62 (d, *J* = 8.4 Hz, 2H, N=CHAr), 8.04 (d, *J* = 8.4 Hz, 2H, N=CHAr), 8.24 (s, 1H, N=CH); ¹³C-NMR (δ, ppm, 125 MHz, CDCl₃): 30.5, 58.9, 64.8, 66.1-72.1, 127.3, 128.2, 128.7, 129.9, 130.2, 131.5, 135.8, 135.9, 149.6, 165.7, 171.5, 171.8; GPC (CHCl₃): *M_n* = 5500, *M_w* = 5600, PDI (*M_w*/*M_n*) = 1.02.

PEG-*b*-PS, 6: Macroinitiator **5** (1.0 g, 0.2 mmol), styrene (10.5 g, 0.1 mol), PMDETA (0.07 g, 0.4 mmol), and Cu(I)Br (0.028 g, 0.2 mmol) were taken in a schlenk tube and degassed by three freeze-pump-thaw cycles. The reaction mixture was then stirred under N₂ at 110 °C for 20 h. After the reaction was complete, it was cooled to room temperature and then precipitated into hexane for two times. The precipitate was further purified by column chromatography (DCM/MeOH; 30:1) to give 2.3 g of imine-functionalized PEG-*b*-PS block copolymer. ¹H-NMR (δ, ppm, 300 MHz, CDCl₃): 0.59-2.20 (br m, Br(ArCHCH₂)_m(CH₃)₂), 3.37-3.96 (br m, ArCOOCH₂CH₂O(OCH₂CH₂)_nCH₃), 4.48 (t, *J* = 4.8 Hz, ArCOOCH₂), 4.79 (s, 2H, CH₂ON=CH), 5.20 (br s, 4H, CH₂ArCH₂), 6.2-7.3 (br m, Br(ArCHCH₂)_m(CH₃)₂CCOOCH₂Ar) 7.62 (d, *J* = 8.1 Hz, 2H, N=CHAr), 8.04 (d, *J* = 7.8 Hz, 2H, N=CHAr), 8.23 (s, 1H, N=CH); ¹³C-NMR (δ, ppm, 125 MHz, CDCl₃): 30.0, 40.1-46.7, 59.4, 64.6, 66.7-72.2, 125.7-128.8, 130.1, 130.4, 131.1, 131.7, 135.1, 136.1, 137.0, 145.4-146.8, 149.8, 166.2, 169.8, 177.4; GPC (CHCl₃): *M_n* = 20000, *M_w* = 22000, PDI (*M_w*/*M_n*) = 1.10.

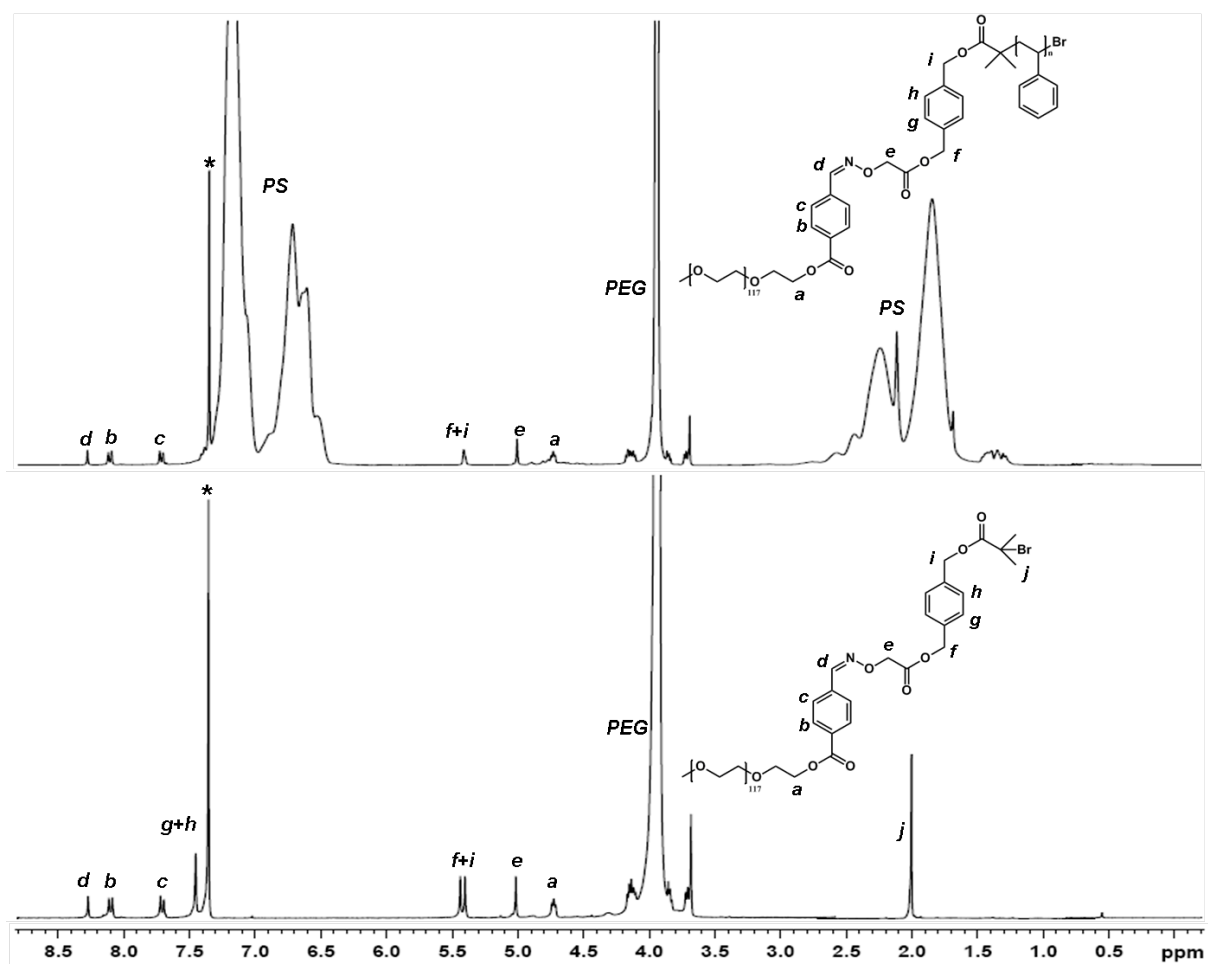


Figure S1. ¹H-NMR spectra of imine-functionalized PEG-PS block copolymer (top) and PEG macroinitiator (bottom). Solvent peak is marked with an asterisk.

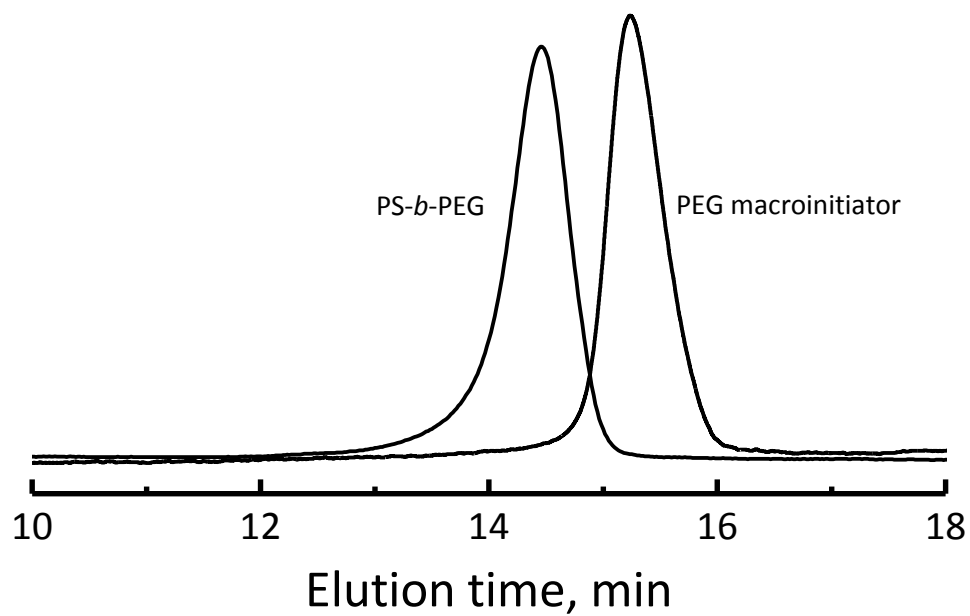


Figure S2. GPC profiles of imine-linked PEG-PS block copolymer and PEG macro-initiator.

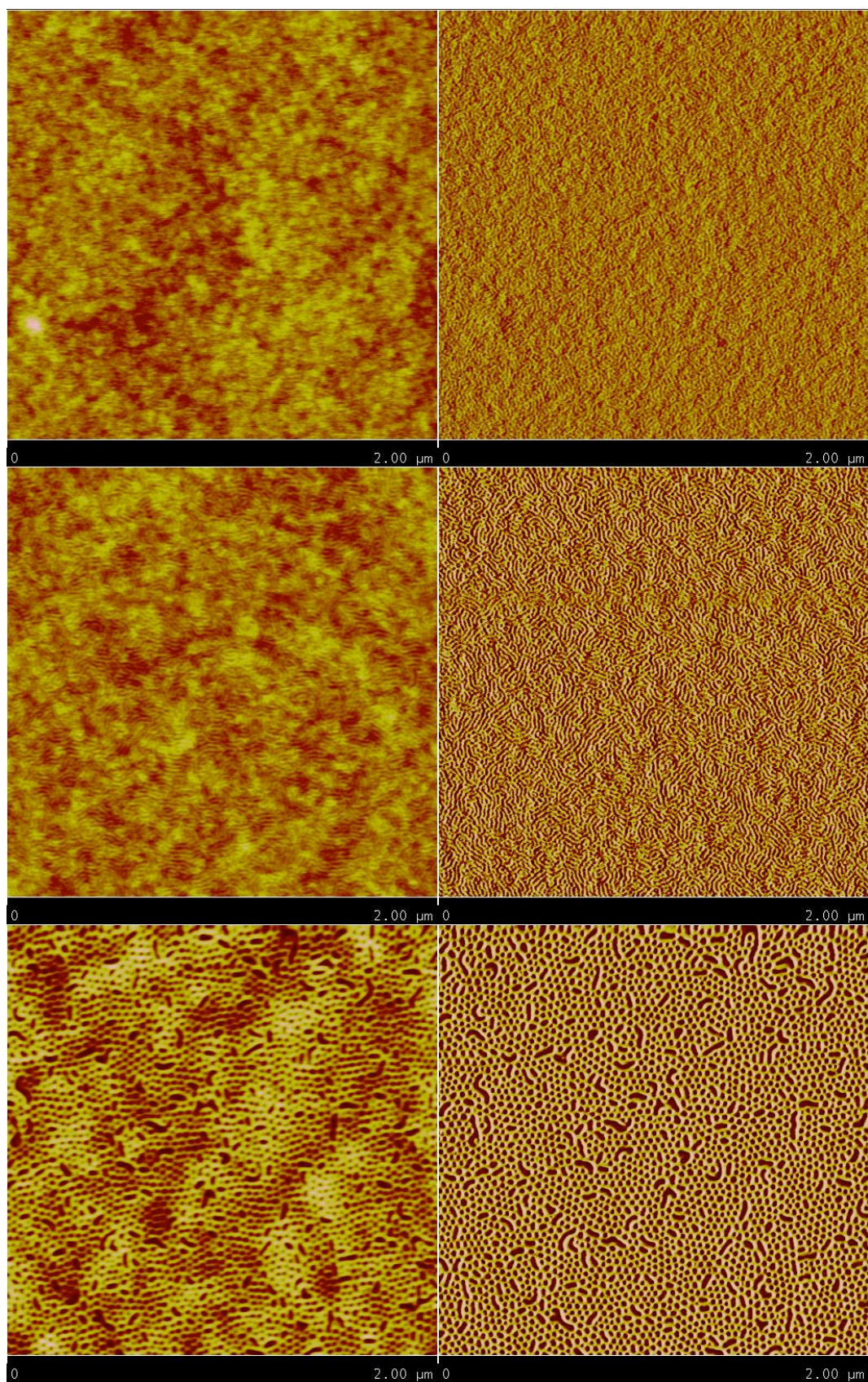


Figure S3. AFM images of PEG-*b*-PS thin film under different solvent annealing conditions: as-spun film (top), annealed without humidity (middle), annealed for 30 min (bottom).

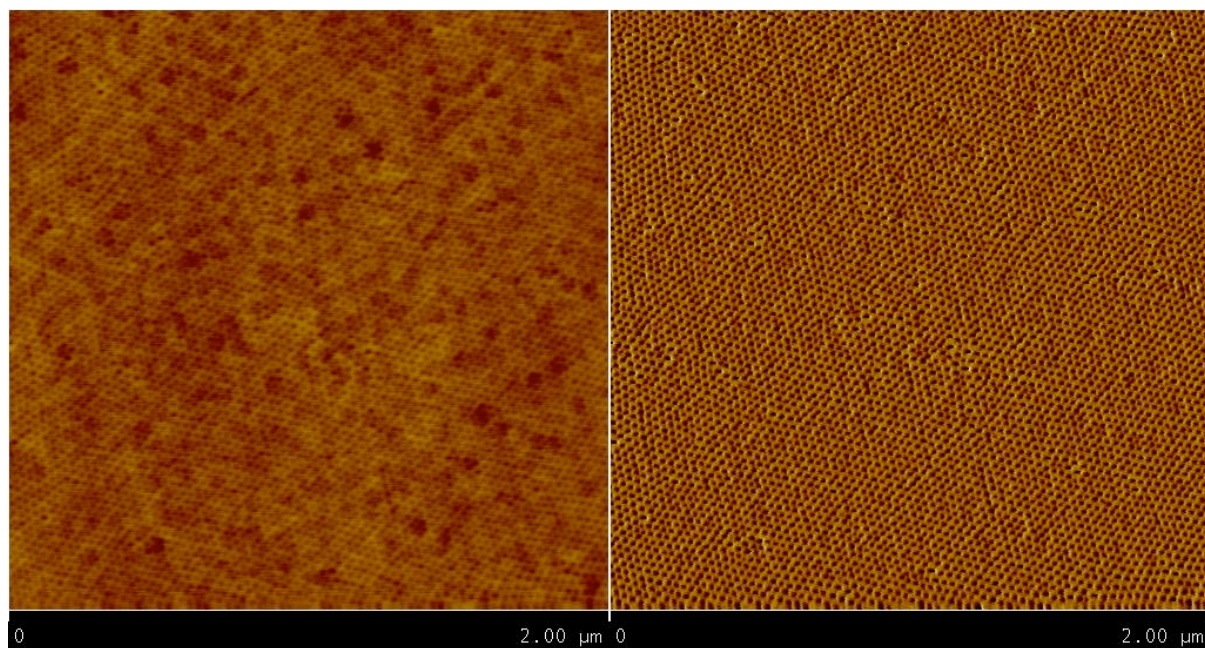


Figure S4. 2x2 μm AFM image.

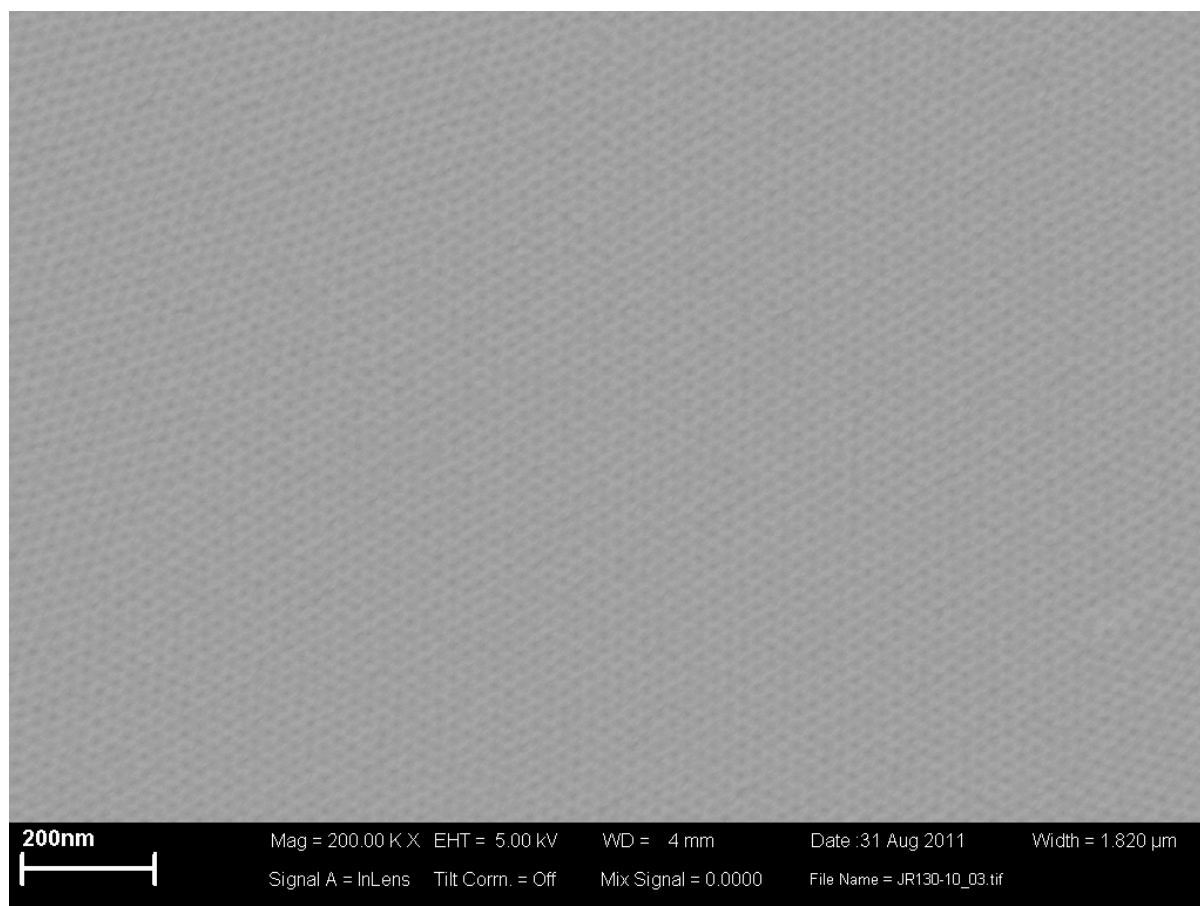


Figure S5. SEM image of the PEG-*b*-PS thin film before TFA treatment.

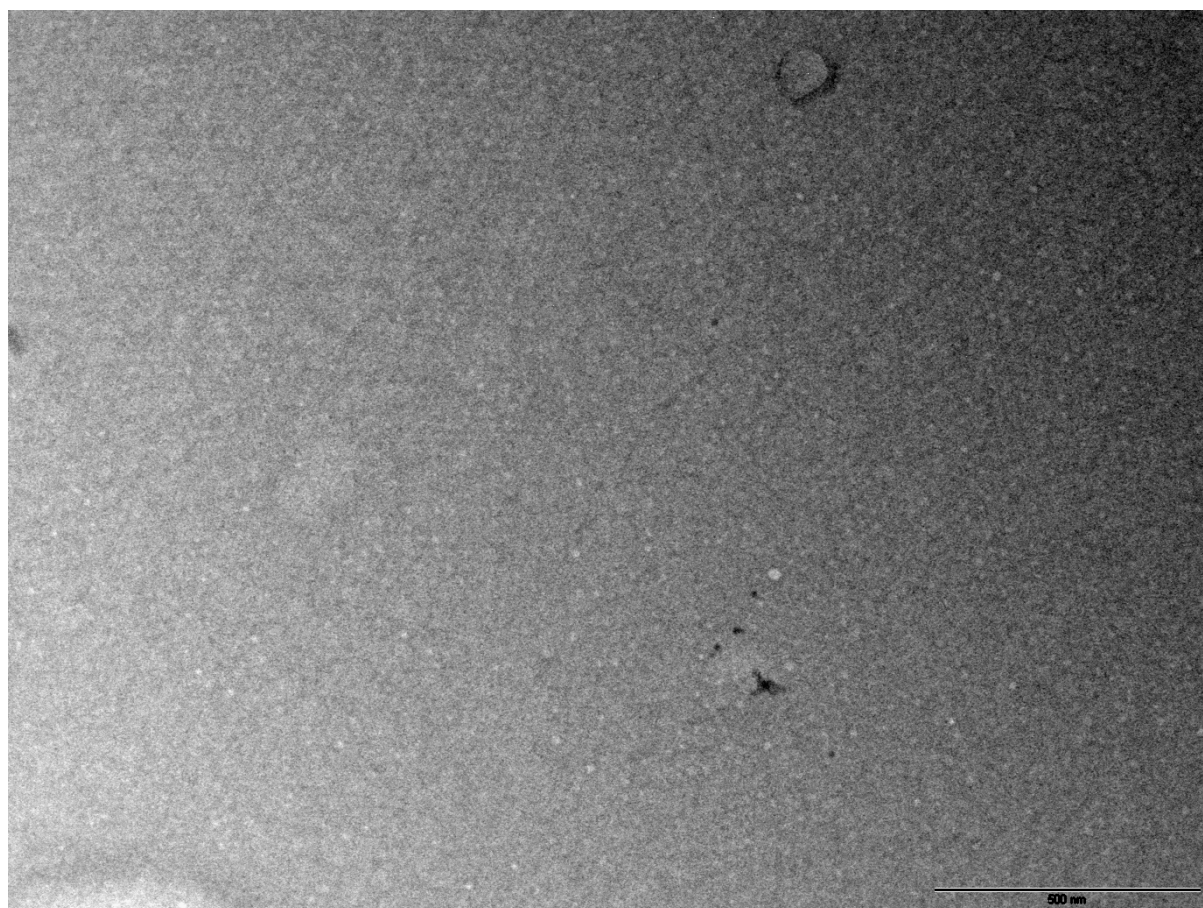


Figure S6. TEM image of the PEG-*b*-PS thin film before TFA treatment.

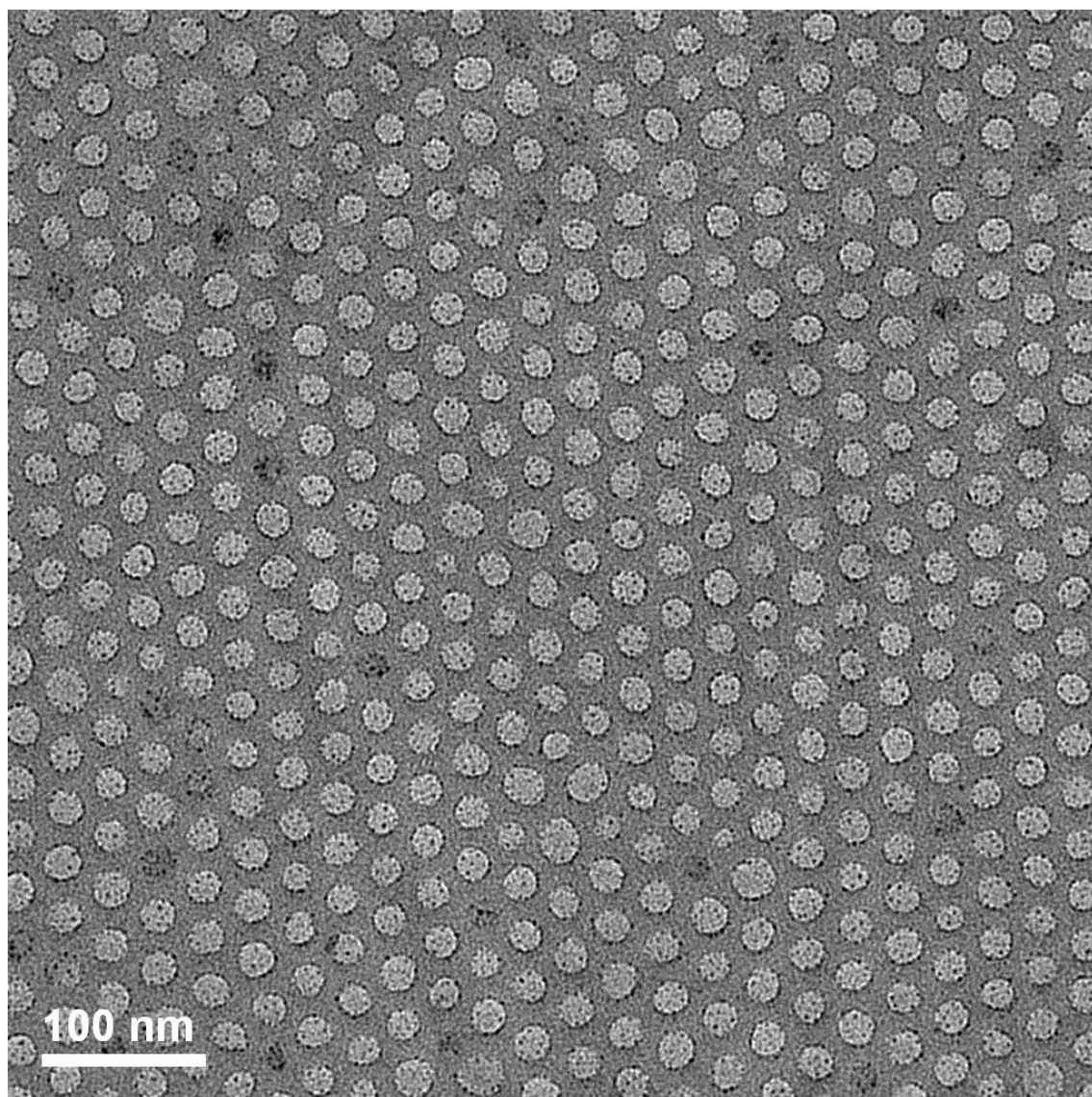


Figure S7. TEM images of the porous thin film after treatment with HAuCl_4 and hydrazine.

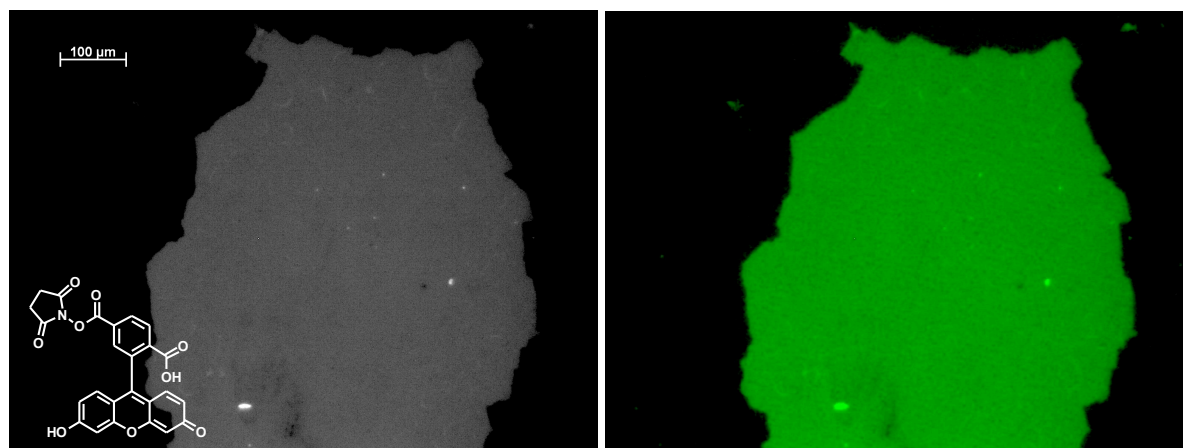


Figure S8. Chemical structure of the activated fluorescein dye and the fluorescence optical micrograph of the polymer film after post functionalization and extensive washing with DMSO.

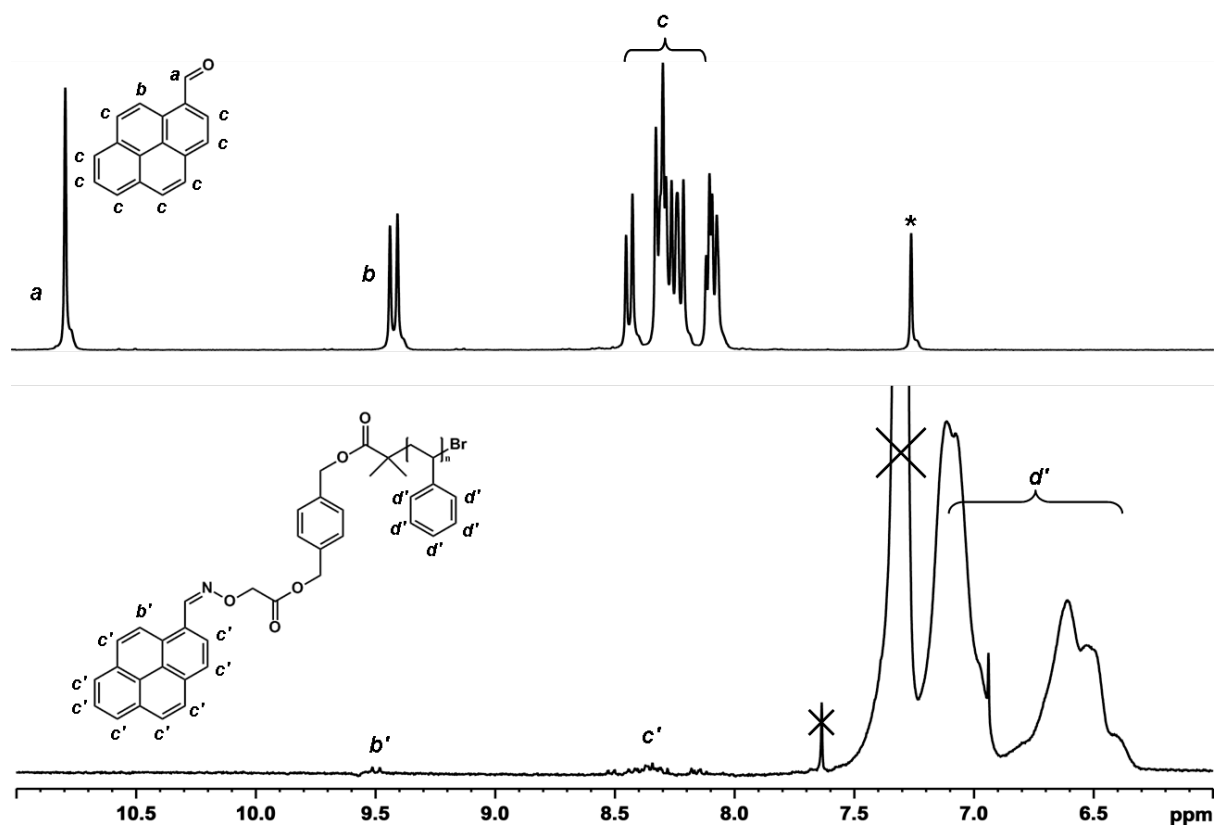


Figure S9. ¹H-NMR of pyrene-3-aldehyde (top) the porous polymer thin film after functionalization with pyrene aldehyde (bottom).

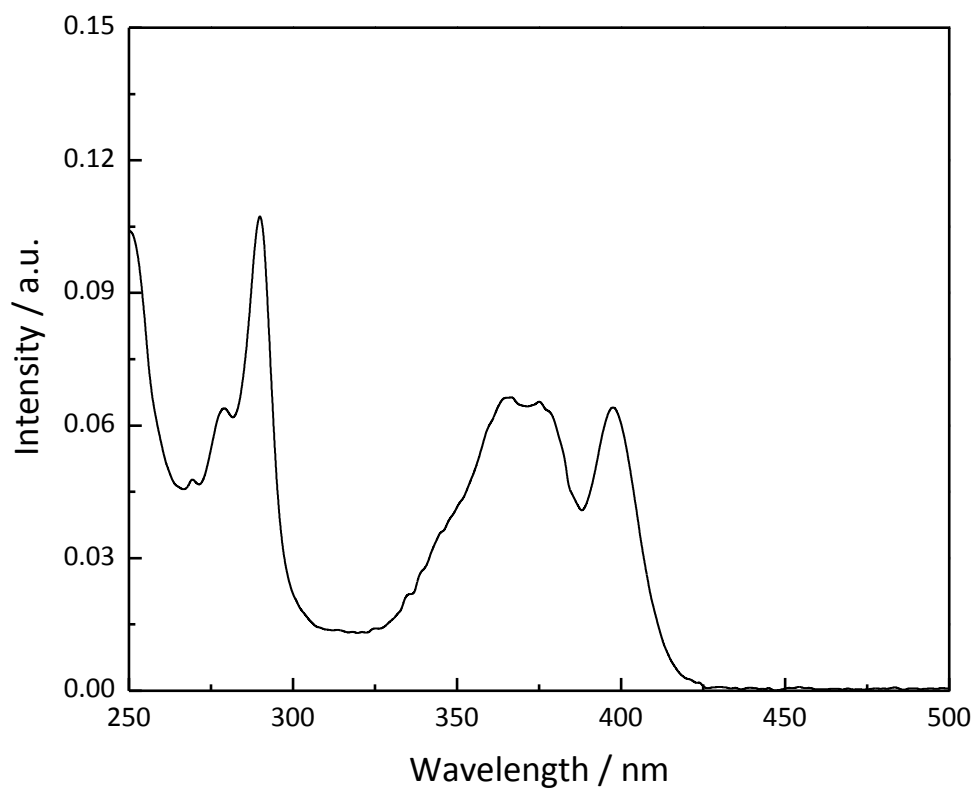


Figure S10. UV-Vis spectra of the porous polymer thin film after functionalization with pyrene aldehyde.

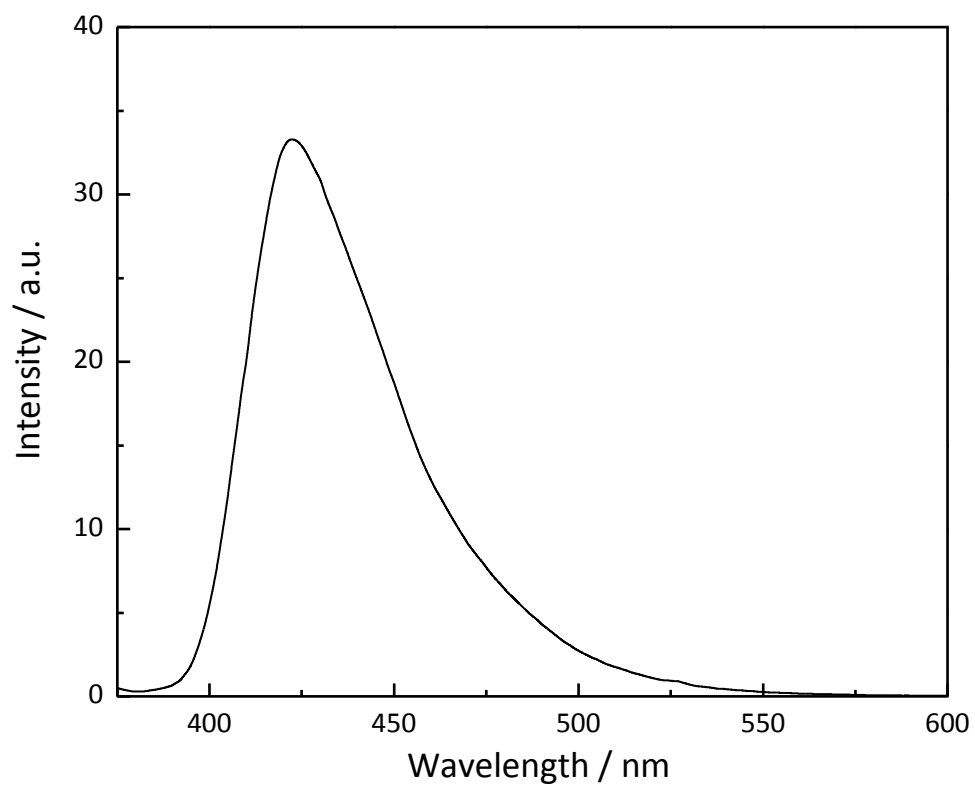


Figure S11. Fluorescence spectra of the porous polymer thin film after functionalization with pyrene aldehyde.

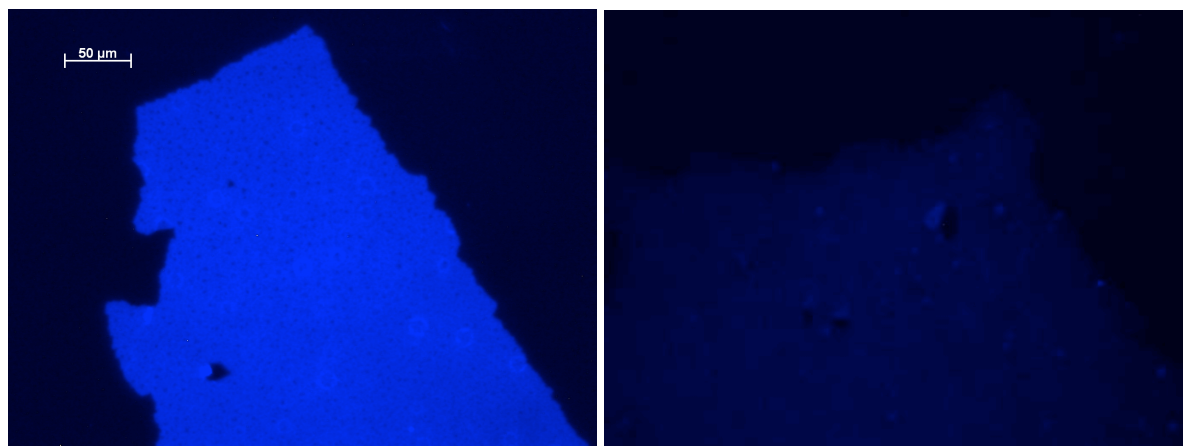


Figure S12. Decrease in emission intensity after partial removal of pyrene from the thin film.

Reference:

1. Peeters, J.; Palmans, A. R. A.; Veld, M.; Scheijen, F.; Heise, A.; Meijer, E. W. *Biomacromolecules* **2004**, *5*, 1862-1868.