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Electronic Supporting Information (ESI)

Remote controllable fiber-type near-infrared light-responsive actuator

Qiuwei Shi,[ad] Jiahui Li,[a] Chengyi Hou,[a] Yuanlong Shao,[ab]* Qinghong Zhang,[c] Yaogang Li,[c] Hongzhi Wang[a]*

[a] State Key Laboratory for Modification of Chemical Fibers and Polymer Materials, College of Materials Science and Engineering, Donghua University, Shanghai 201620, P. R. China. E-mail: wanghz@dhu.edu.cn;

[b] Cambridge Graphene Center, Department of Engineering, University of Cambridge, Cambridge, UK. E-mail: yuanlong.shao@gmail.com;

[c] College of Materials Science and Engineering, Donghua University, Shanghai 201620, P. R. China;

[d] Current Address: Energy Sciences Institute II, Yale University, West Haven, Connecticut 06516, United States.

Experimental section

Materials

Graphite powders (500 meshes, purity: 99%) was purchased from Shanghai Yifan Graphite Co. Ltd (China). Potassium permanganate, sulfuric acid, hydrogen peroxide (30 vol.%), hydrochloric acid, sodium polyacrylate (PAAS) and ethyl alcohol (95 vol.%) were purchased from Sinopharm Chemical Reagent

Co. Ltd (China). Polytetrafluoroethylene capillary (diameter: 500 μm) were purchased by Shanghai Zhou Tong Electrical Equipment Co. Ltd. (China).

Synthesis of PAAS/graphene oxide composite fiber

Graphite oxide powders were firstly prepared by oxidation of natural flake graphite on the basis of the modified Hummers' method. Then different concentration of GO dispersion were obtained after stirring and ultrasonication. The PAAS/GO composite fibers (P/GO fiber) were synthesized through wet-spinning method. Typically, the GO dispersion (10 mL, 2 mg/mL) and PAAS (0.2 g) were mixed and further magnetically stirred and variable frequency oscillation to fabricate the spinnable PAAS/graphene oxide hydrogel. The PAAS/graphene oxide hydrogel was injected in ethyl alcohol (95 vol.%) solution at a speed of 6 mL h^{-1} to form P/GO aquagel fiber.

Fabrication of torsional P/GO fiber

The P/GO fiber was obtained after water extraction process of P/GO aquagel fiber in ethyl alcohol solution for 10 min. Then one end of P/GO fiber was anchored to a digitally controlled electric motor. The other end was anchored to a piece of plastic flake. The tP/GO fibers with different rotation degrees were obtained by controlling the rotation speed and time of the electric motor.

Characterization and Measurements

The morphologies of the as-prepared P/GO fiber and tP/GO fiber were measured using a field emission scanning electron microscopy (FESEM, HITACHI S4800) at 10.0 kV. The videos and photographs of actuation behavior of tP/GO fiber were taken with a charge coupled device (CCD) video camera EOS D7000, Nikon. The two-dimensional X-ray diffraction (2D XRD) patterns and spectroscopy were characterized on a Bruker D8 diffractometer with Cu Kα irradiation (λ = 1.5406 Å) with and a VÅNTEC-500 Area Detector. The operating voltage and current were 40 kV and 40 mA. Attenuated total reflectance-infrared (ATR-IR) spectra were recorded on a Nicolet NEXUS-670 spectrometer. The infrared thermal images and temperature curves were performed by a FLIR Automation & Science Cameras A300 infrared thermometer.

1. Supporting Figures

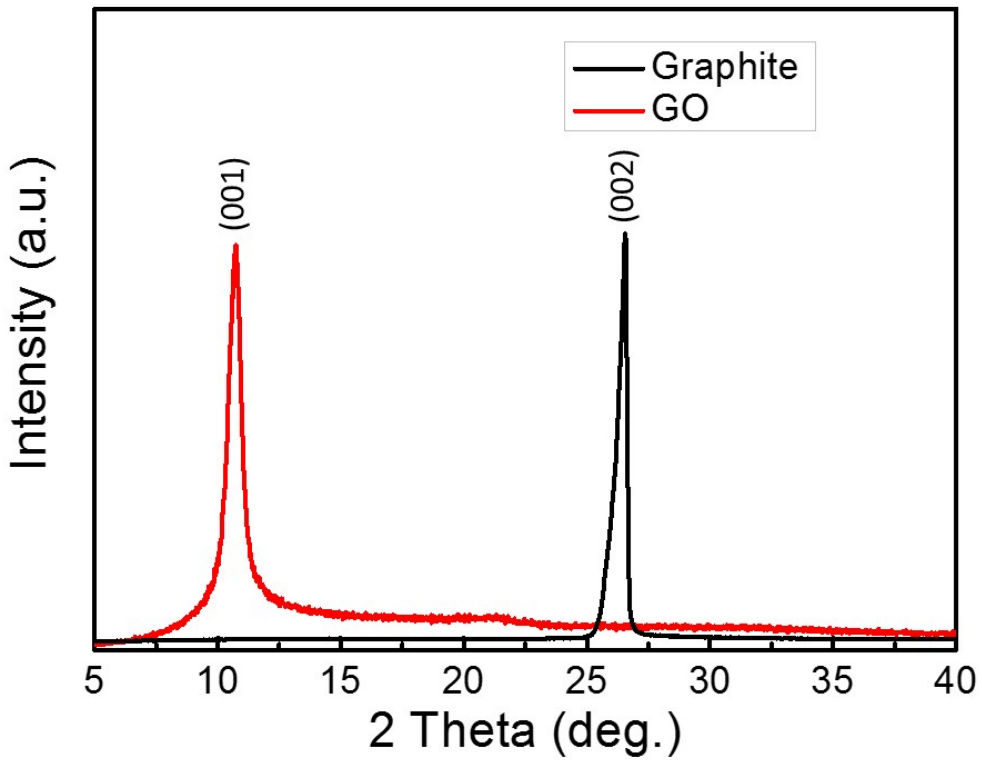

Figure S1. XRD patterns of the graphite and GO. The crystalline XRD patterns of graphite and GO demonstrated the oxidation of the graphite. The characteristic peak of GO was at 10.4° corresponding to the crystal plane (0 0 1). The characteristic peak of graphite was at 26.5° corresponding to the crystal plane (0 0 2).

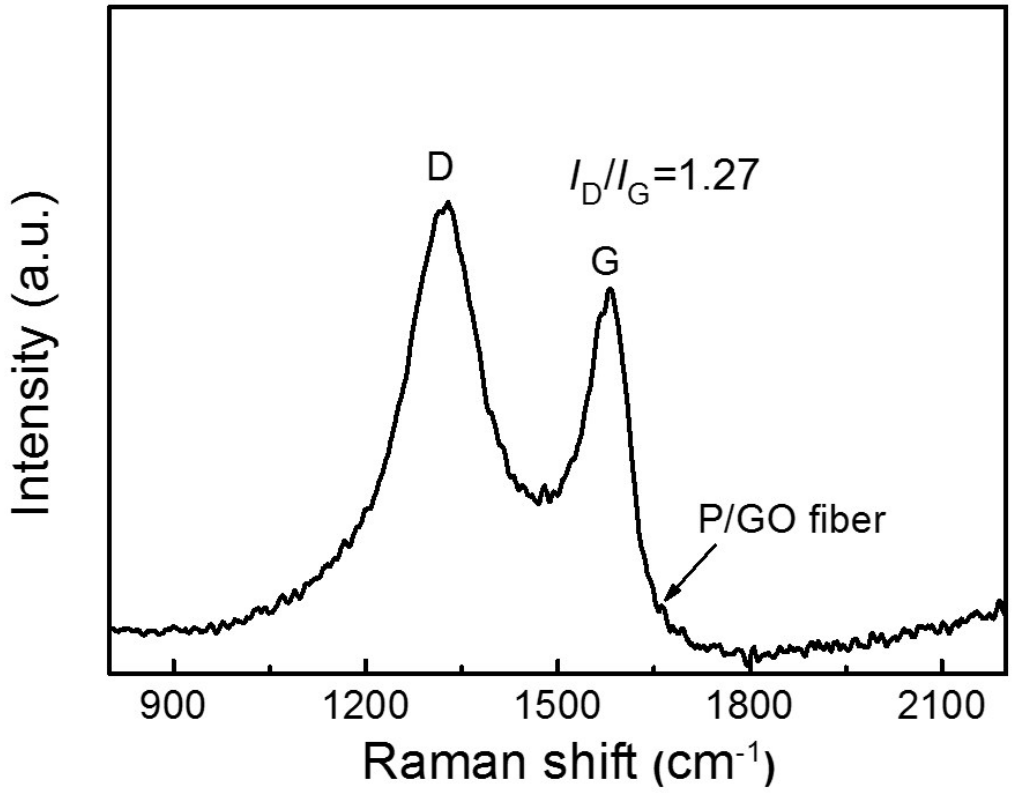

Figure S2. Raman spectrum of the P/GO fiber. The Raman spectra of the P/GO fiber consists of distinct D and G band, which are the breathing modes of six-atom rings and the high-frequency E_{2g} phonon at Brillouin zone centre. The intensity ratio of the D and G bands P/GO fiber is 1.27 (similar with the value GO).

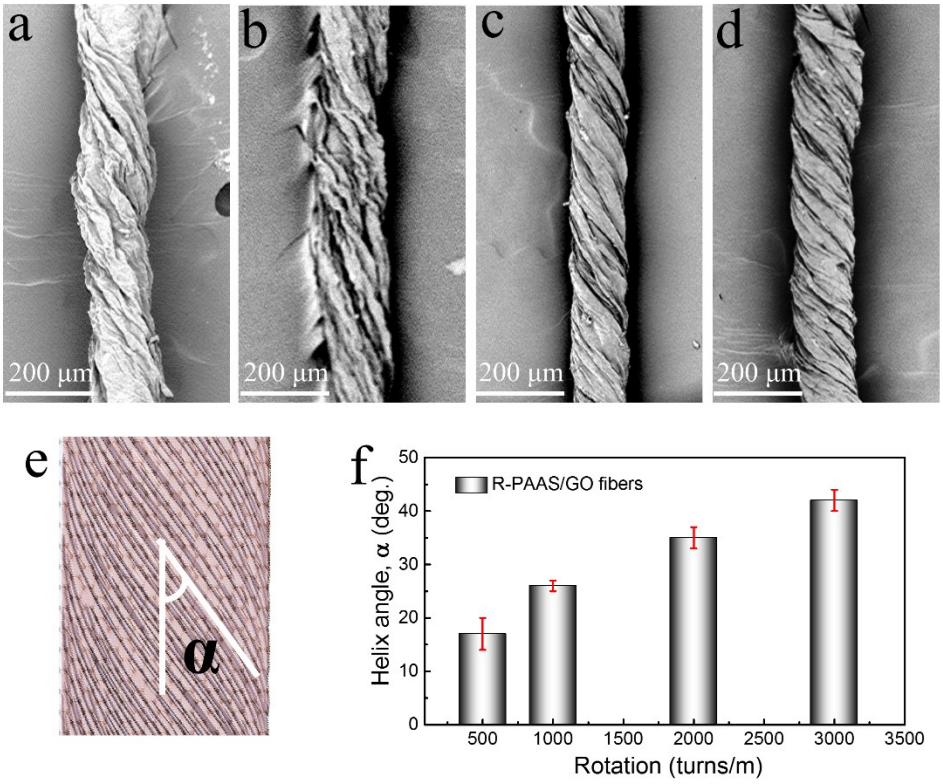

Figure S3. (a–d) FESEM images of tP/GO fibers with different rotation degrees of 500, 1000, 2000 and 3000 turns per meter; (e) Scheme of measurement of helix angle (α); (f) Measured helix angle (α) with different rotation degrees of tP/GO fiber.

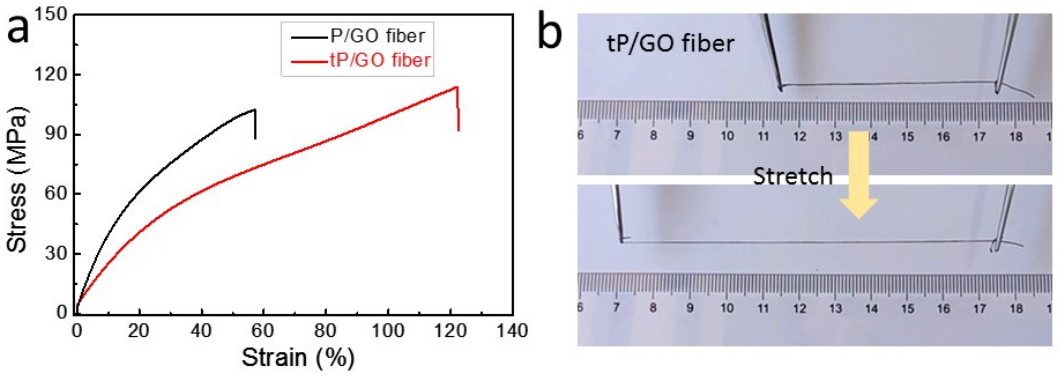

Figure S4. (a) Tensile stress of the obtained P/GO fiber and tP/GO fiber (with rotation degree of 3000 turns). (b) Photographs of stretching performance of tP/GO fiber. The measured tensile stress of P/GO fiber and tP/GO fiber are up to 102.4 (black line) and 113.9 (red line) MPa, respectively. With the rotated treatment, the tensile strains accordingly increase from about 57% to 122% while the tensile stress of tP/GO fiber have also increased for 11.2%. The mechanical flexibility allows the tP/GO fiber to stretch to more than 100% strain without any damage. The well mechanical properties of tP/GO fiber endow it possibility to use in a fabric and even smart clothing.

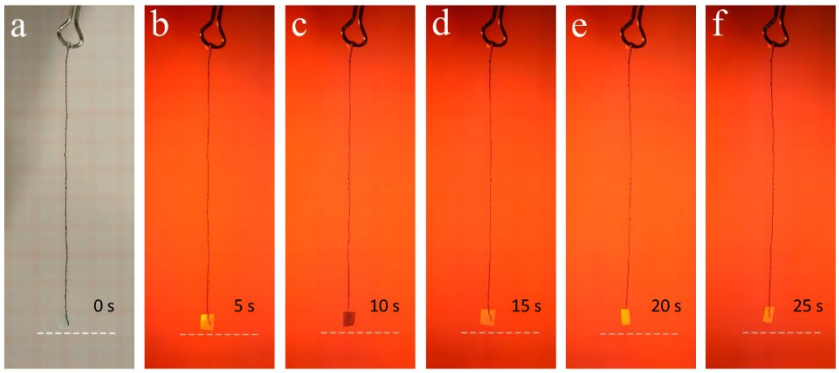

Figure S5. Sequential photographs of the displacement of one end of a 10 cm long tP/GO-3 fiber under NIR light irradiation (50 mW cm^{-2}).

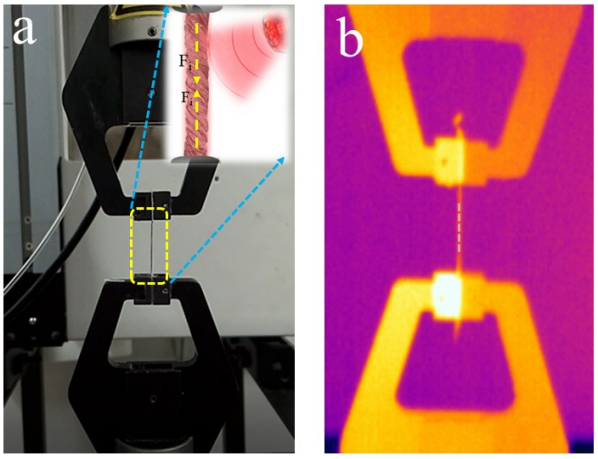

Figure S6. Photographs of tensile stress measurement by the universal testing machine (Instron 5969) and the corresponding representative infrared thermal image with NIR light irradiation. Two ends of a 2 cm long tP/GO-3 fiber were fixed with the clip of the universal testing machine. The NIR light irradiation switched on/off with the intervals about 45 s. The tested maximum force was up to 0.13 N. Simultaneously, the infrared thermometer was used to record the temperature.

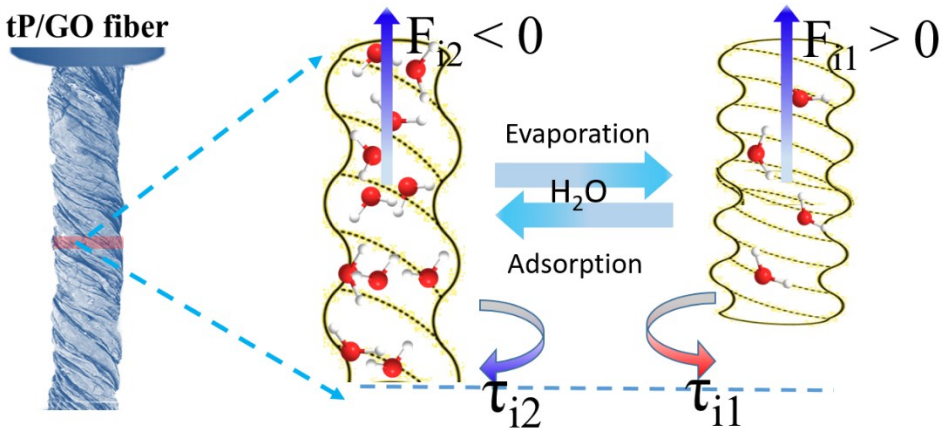

Figure S7. Schematic drawing of the rotation and back rotation of tP/GO fiber with simplified loading forces during the water evaporation and adsorbtion.

2. Supplementary Note:

Calculations of the power output and power efficiency of the tP/GO-3 fiber actuator:

The power efficiency ($\eta = {P_{output}}/{P_{input}} \times 100\%$) of the tP/GO-3 fiber actuator is defined as the power output (P_{output}) during the deformation of the fiber divided by the power input (P_{input}) of NIR light irradiation.

The P_{input} was evaluated as the effective light power of NIR light irradiation:

$$P_{input} = I_{NIR} \cdot A \quad \text{(S1)}$$

where I_{NIR} is the NIR light power density (50 mW cm^{-2}), A is the effective irradiation area (1.65×10^{-1} cm^2). The P_{input} is calculated to be 8.25 mW.

The P_{output} of the tP/GO-3 fiber actuator when lifting the plastic film was approximated as:

$$P_{output} = E_{output}/t = (mv^2/2 + mg\Delta h)/t \quad \text{(S2)}$$

where E_{output} is the output energy, t is the NIR irradiation time (25 s), m is the weight of the plastic film (81 mg), v is the speed of the plastic film during rising process (0.21 mm s^{-1}), Δh is the lifting distance (4.9 mm). The power output (P_{output}) is calculated to be 0.158 mW.

The power efficiency (η = 0.158 mW/8.25 mW × 100%) of the the tP/GO-3 fiber actuator was calculated to be 1.91%.

Supplementary Video S1. The real-time video of the photo-driven rotating behaviour of tP/GO-3 fiber corresponding to the infrared thermal images.

Supplementary Video S2. The real-time infrared thermal images of the photo-driven rotating behaviour of tP/GO-3 fiber.

Supplementary Video S3. The real-time infrared thermal images of the photo-driven rolling behaviour of tP/GO-3 fiber.

Supplementary Video S4. The real-time video of the photo-driven bending behaviour of a piece of cotton fabric knitted with three pieces of tP/GO-3 fibers.

Supplementary Video S5. The real-time video of the displacement of one end of a 10 cm long tP/GO-3 fiber under NIR light irradiation.