

Supplementary Information

4D Thermomechanical Metamaterials for Soft Microrobotics

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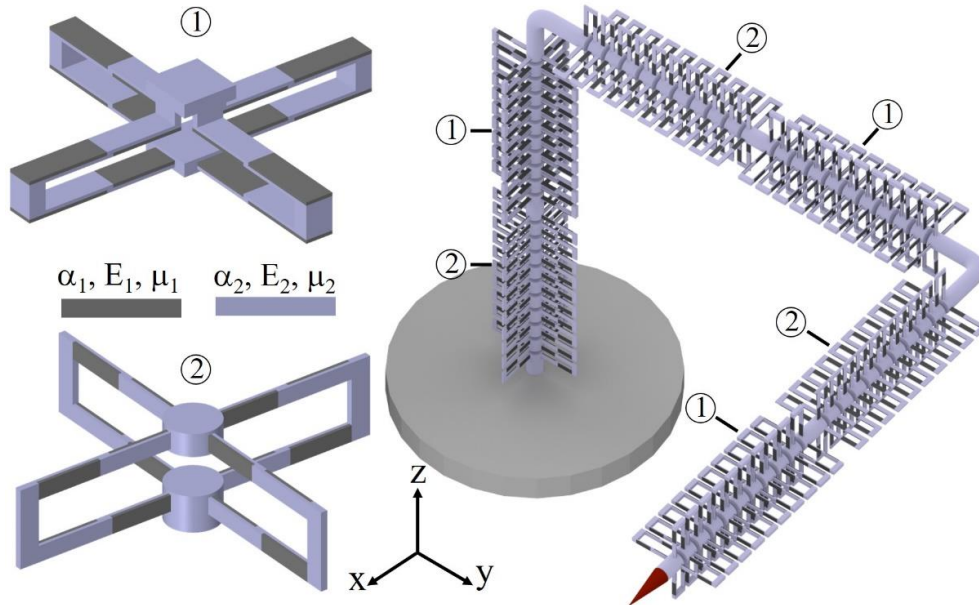
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Supplementary Concept Design

We have designed two kinds of functional structures: a rotational element and a translational one. These elements can further assemble into a microrobot. It is tempting to fabricate such a microrobot and experimentally characterize its thermally induced performances. However, we note that we use a viscous monomer that is exposed to a Two Photon polymerization. After the writing one has to remove the remaining resist which is very fragile (very long structure) can be a killer. In the future work we aim at assembling 3 modules containing rotational and translational parts using micro-assembly process. In principle one could try to 3D print it directly, but this will strongly affect the quality via the resolution.



Supplementary Figure 1. A conceptual microrobot consists of a three-dimensional assembly of rotational and translational elements. Along each axis, rotation and translation are produced upon temperature changes. Accumulation of these motions along each axis leads to mobility of the tip end (marked in red). The micro robotic arm can position the tip end in space controlled by external temperature changes.

Supplementary Mechanical Properties Measurement

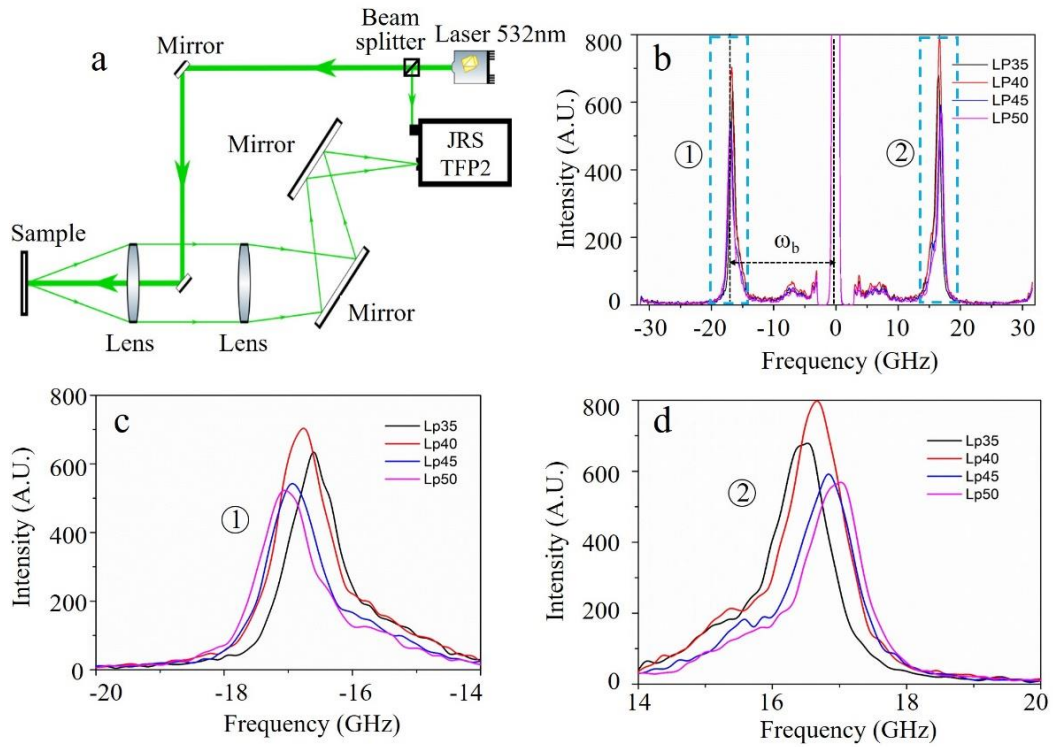
The mechanical properties (Young's modulus E) for different laser powers were obtained by measuring bulk polymer cuboid samples (side length 50 μm , made from IP-Dip, Nanoscribe GmbH). We used the Brillouin light scattering to measure the longitudinal elastic modulus, following

$$M = \rho \left(\frac{\lambda \omega_b}{2n \sin\left(\frac{\theta}{2}\right)} \right)^2$$

where λ and θ are the wavelength and angle between the incident and scattered wave vectors, taken to be 532 nm and π , respectively. Refractive index n and density ρ are 1.5534 and 1000 kg m^{-3} , respectively. The Brillouin frequency shift was measured based on the frequency difference between the Rayleigh and the Stokes peaks, as described below. Young's modulus was then obtained from

$$E = M \frac{(1 + \nu)(1 - 2\nu)}{(1 - \nu)}$$

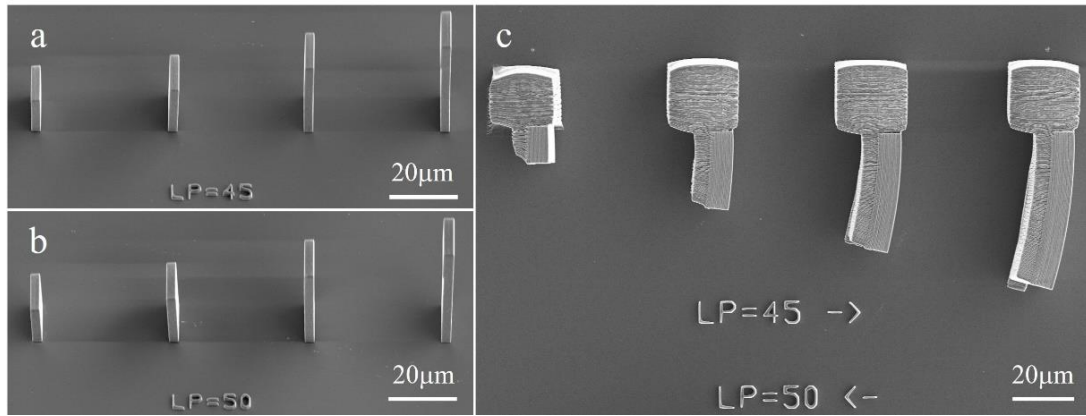
where ν is Poisson's ratio taken as 0.4 here.



Supplementary Figure 2. Measurement of mechanical properties. (a) Schematic of the Brillouin microscope. (b) The Brillouin frequency shift ω_b of longitudinal phonons is determined as the peak of the scattered intensity. (c, d) Magnified views of the left and right peaks, where the frequency differences between different cubes are clearly observed.

Supplementary Fabrication Technique

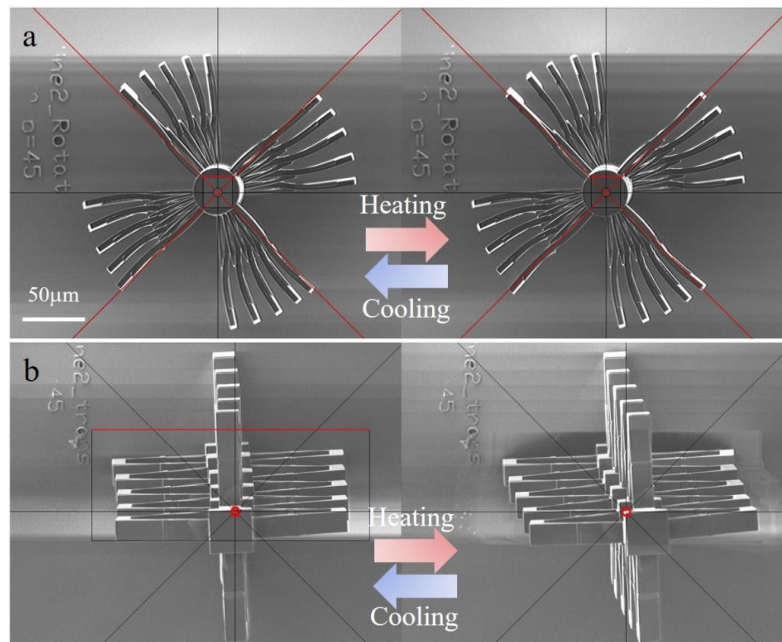
We fabricate two-component beams using different laser powers, and single component beams as references. Pre-bending of the bi-material beams is observed and originates from the different volume shrinkages of the two different components during development.



Supplementary Figure 3. Conceptual proof of the principle of the fabrication of two different components with a single photoresist but different laser power. Electron micrographs of (a, b) beams fabricated by single laser exposure power and (c) two-component beams fabricated using different laser powers. The beam lengths from smallest to largest are 10 μm , 20 μm , 30 μm and 40 μm , respectively. In the images, "LP" is the abbreviation of exposure laser power and the numbers denote the power scaling factors as a percentage of a nominal power.

Supplementary Conceptual Testing

We present actuation of the functional stack using an electronic beam as external stimulus. In the heating stage, the electronic beam exposure lasted around 10 seconds while the natural cooling stage lasted around 60 minutes. This process was conceived to conceptually and visually show the actuation mechanism. Due to the nature of heat diffusion and the fact that polymers are bad heat conductors, motion is mainly observed at the top layer. Considering the inaccuracy in controlling temperatures and heating/cooling speed, we quantitatively characterized actuation in an enclosed chamber (see main text) under well controlled external thermal conditions.

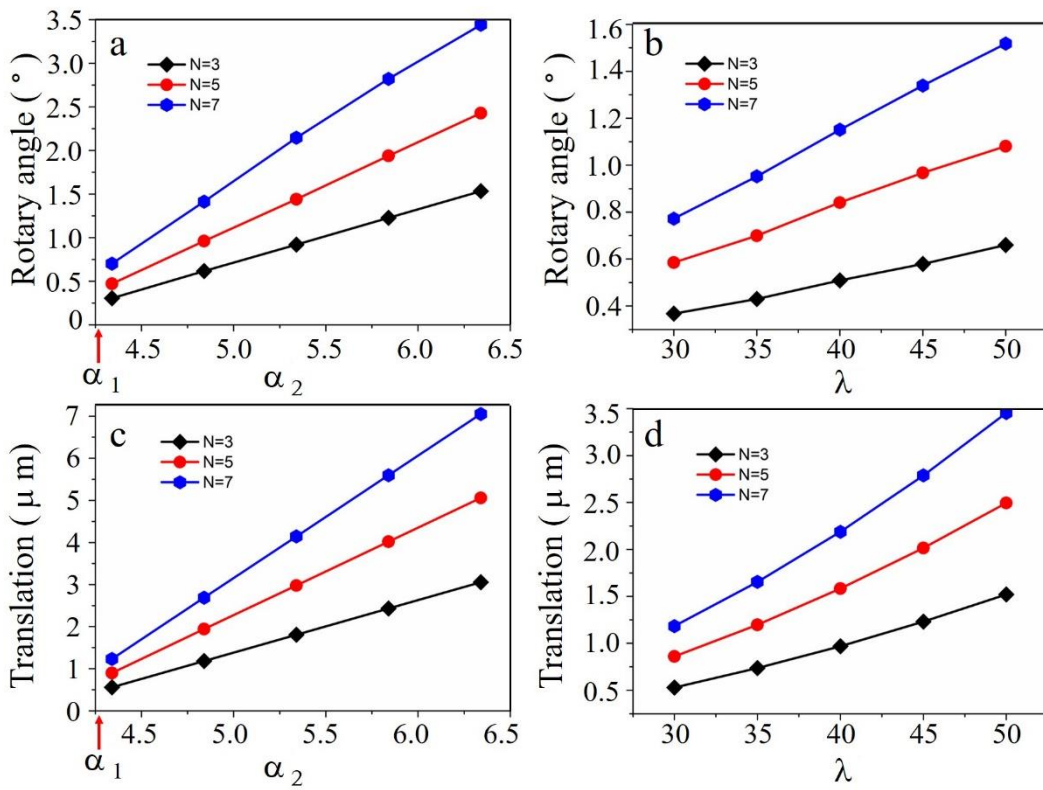


Supplementary Figure 4. Conceptual validation of the actuation mechanism of (a) rotary lattices and (b) translation lattices. The thermal stimulus was applied on the top end of the structures by electronic beam exposure. When the thermal stimulus was set on, the structures

showed overall motion; when the stimulus was set off, the relative deformation and motion disappeared gradually, demonstrating a sensitive and reversible thermal-driven process. The red cross-lines in panel (a) and the central circle are added to make deformations clearer.

Supplementary Parameter Analysis

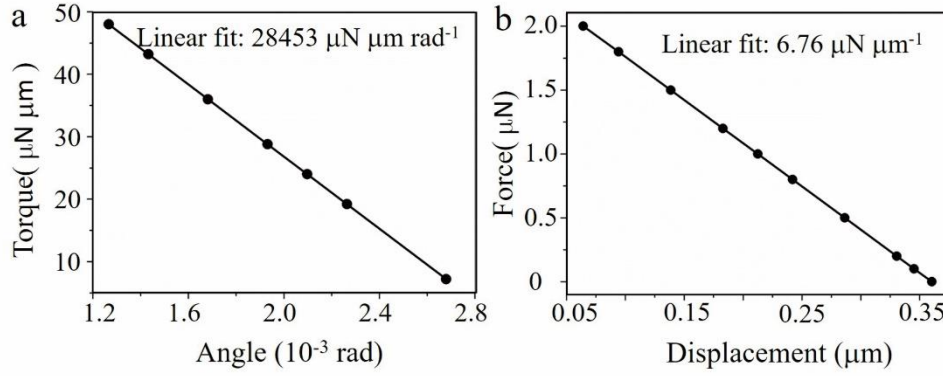
We have shown in the main text that thermally induced motion is well controlled by external temperature changes. The motion amplitudes are also influenced by other factors, such as thermal expansion properties and geometry parameters. We quantitatively analysed the influence of these parameters, as shown in the following figures. The rotation angle is observed to be proportional to the difference of thermal expansion coefficients and to the aspect ratio of the bi-material beams. A similar relationship is observed in the translation structure. It is clear that amplitudes of motion can be effectively adjusted by selecting structural or material parameters.



Supplementary Figure 5. Influence of key parameters on motion amplitude. (a, c) Dependence of motion amplitude on thermal expansion coefficients for structures with 3, 5 and 7 layers, respectively. Note that α_1 is fixed and marked out in red, while α_2 is varied. (b, d) Dependence of motion amplitude on geometrical properties for structures with 3, 5 and 7 layers, respectively. Here we define the aspect ratio as $\lambda = \frac{L_1+L_2}{h_1+h_2}$, or the ratio between length and thickness for the bi-material beam. Geometrical nonlinearity has been accounted for.

Supplementary Actuation Performance

We estimated the actuation torque/force that the structure can exert to move an object. In the simulations, we set one end of the unit cell as fixed and exerted an inverted torque (force) on the free end. A thermal gradient of 20 K was imposed to study the thermal-mechanical behavior. Motional responses were obtained and are plotted in Supplementary Figure 6.

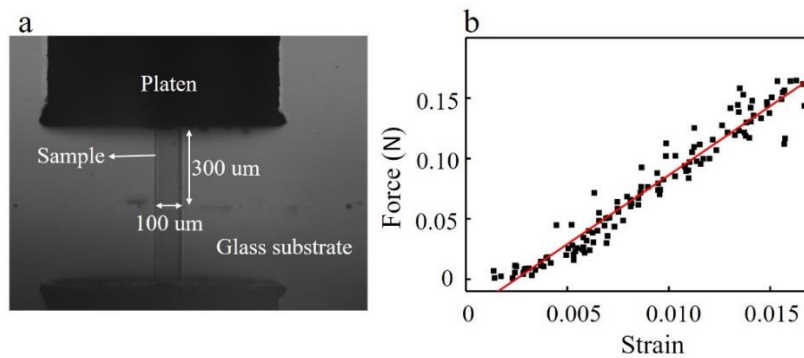


Supplementary Figure 6. Actuation behaviour of (a) the rotary cell and (b) the translational cell. Clearly, the work offered by the structure under thermal stimuli is finite: the larger the load, the smaller the motion amplitude. We calibrate the cells as Hooke's springs and obtain the torsion coefficient (stiffness) for the rotary (translational) cell by linear fitting as $28453 \mu\text{N } \mu\text{m rad}^{-1}$ ($6.76 \mu\text{N } \mu\text{m}^{-1}$).

In the main text, we mentioned that the elastic limit is not reached. To evaluate the validity of the linear regime, we have included geometrical non-linearity in the numerical calculations. After the computation we checked the local peaks in the strain which never exceeds 0.23%. An estimation on the Maximum strain that falls into the linear elastic stage is then needed.

We have fabricated bulk polymer samples (side length $100 \times 100 \times 300 \mu\text{m}$) and obtained their mechanical responses in compression experiments. As shown in following figure, the samples are placed between a fixed glass substrate and a flat loading device. The loading device is driven by a stepping motor with an attached force sensor. A digital camera equipped with a $20\times$ objective lens facing the sample is used to monitor the deformation of the faces and hence to measure the strain. The true strain is obtained via image cross correlation. Experiments are carried out at a speed of 0.001 mm s^{-1} , during which the applied displacement increases gradually.

We observe linear relation between the force and corresponding strain, demonstrating that the material is still within the linear elastic stage when the strain reaches 1.5%. Assuming our material as linear in expansion up to 1.5% the previous claim is justified.

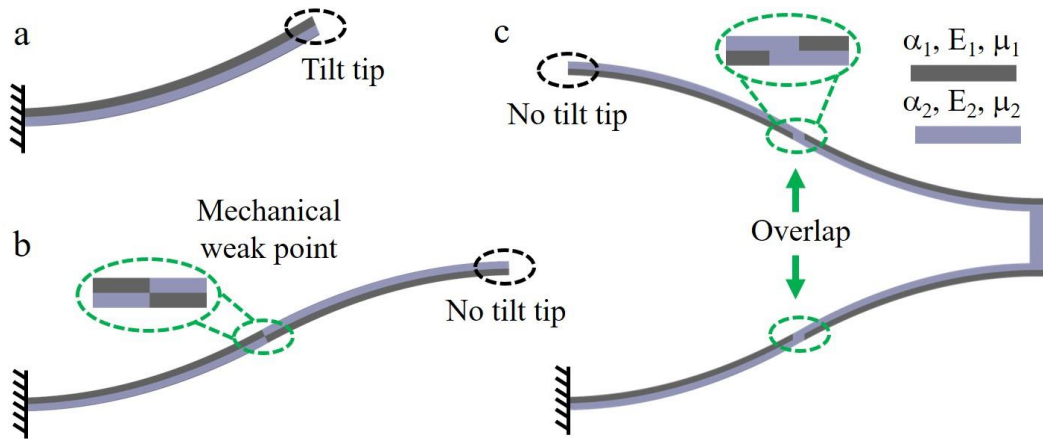


Supplementary Figure 7. Compression experiments. (a) The setup to perform compression testing. (b) The obtained results between imposed force and corresponding strain.

Supplementary Sample Design

To obtain larger motional amplitude, we did some optimization of the bilayer beams. The optimized structure features two advantages: (1) the structures can achieve larger actuation

amplitudes in the desired direction (here the vertical direction) under thermal stimuli; (2) the structure is mechanically more robust and more easily fabricated with the designed overlap [1].



Supplementary Figure 8. Design of the thermomechanical structure: (a) Schematic of a simple single bilayer beam showing the tangential tilt end in response to a temperature change. (b) Two bilayer beams with inverted layer compositions are connected to form an S-shaped beam. (c) The proposed structure with an overlap shows no tilt angle at the end of the beams. It is also mechanically more robust.

[1] K. Jia, S. Pal, H. Xie, An electrothermal tip-tilt-pistonmicromirror based on folded dual S-shaped bimorphs, *Journal of Microelectromechanical systems* 18 (5) (2009) 1004-1015.