Shape-morphing materials

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Painting on programmable reconfigurable metastructures

Zixiao Liu & Ximin He

Lattices of micrometre-sized metamaterials embedded in thermoresponsive hydrogels deform upon heating to reveal encrypted images from a blank gel canvas.

Materials scientists endeavour to achieve object reconfiguration in a programmable manner – the transformation of initially identical and featureless geometries into a myriad of shapes. However, encoding intricate details from complex two-dimensional or three-dimensional objects into seemingly bland ones presents a substantial challenge for artificial materials. The resulting shapes often maintain some connectivity with their initial designs[1], which is not favourable for encryption and anticounterfeiting applications. Now, writing in *Nature Materials*, Mingchao Zhang and colleagues[2] overcome this challenge by encoding two-dimensional graphic information within a smart metastructure, specifically an array of micrometre-sized lattices embedded in a thermoresponsive hydrogel film. Upon heating, the lattices are deformed by the contraction of the hydrogel 'muscle'. Leonardo da Vinci's masterpiece the *Mona Lisa* can be concealed within a seemingly ordinary hydrogel 'canvas' at room temperature, but when warmed, each individual lattice deforms into a certain shape as encoded (Fig. 1a). When viewed by the naked eye, these reconfigured lattices

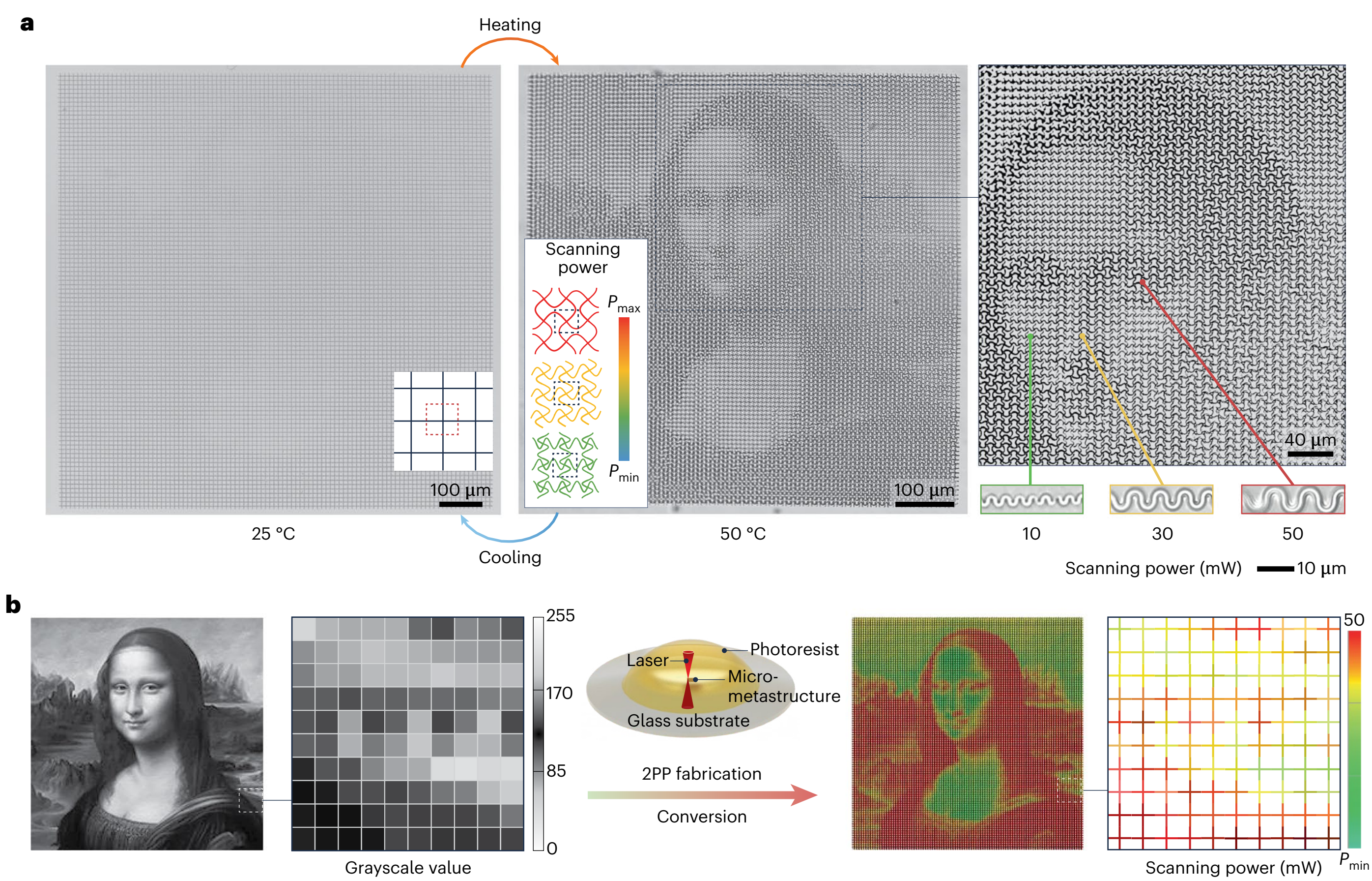

Fig. 1 | Highly programmable stimuli-responsive metamaterials. a, Optical images and schematic illustrations of a 3D-printed reconfigurable metastructure with the *Mona Lisa* encoded at 25 °C and 50 °C. **b**, Pixel-by-pixel mapping of 10,000 square micro-architected metalattices with different laser scanning powers, converting the corresponding grayscale values into distinct pixels with different reconfigurability. Figure adapted from ref. 2, under a Creative Commons license CC BY 4.0.

show da Vinci's masterpiece and may even transform further into Johannes Vermeer's painting the *Girl with a Pearl Earring* and other famous paintings depending on the encoding.

The transformation process from one object into another is realized through the changes of a large number of geometrical details: for example, the position, curvature and angle change of each elementary unit undergoing various deformation modes such as bending, twisting and buckling, all of which are tailored to each individual location[1,3]. In principle, the inverse design of high-resolution reconfiguration requires pixelating a bulk material into an architected structure composed of individually deformable, small elementary units, such as micropillars[3], plates[4], lattices[2] and kirigami cuts[5]. Such an architected structure may act as a 'skeleton': passive but deformable by a separate responsive 'muscle' material[3,4,6], or itself may be made of a stimuli-responsive material and able to reconfigure upon environmental cues[1,5–9]. In the field of soft-material morphing, these architected structures have demonstrated their abilities to generate a variety of morphing patterns by the following approaches: (1) by strategically arranging materials with varying responsiveness and adjusting their geometrical parameters, the architected structure can exhibit distinct in-plane and out-of-plane configurations, resulting in enhanced diversity of structural morphologies[8,9]; (2) as inherent defects sometimes produce morphing patterns that differ from those of defect-free regions, by systematically identifying and precisely arranging these defects within materials, specific patterns can appear and vanish in response to stimuli[3,7]; (3) by translating target object information into a spectrum of fabrication parameters, different locations acquire diverse material properties such as aspect ratio, stiffness and mechanical instability[1,2,10], leading to a range of manifested deformations. Zhang and colleagues harnessed the third strategy to develop their skeleton–muscle metamaterial system.

Zhang and colleagues embedded a micro-lattice skeleton within a layer of thermoresponsive hydrogel muscle. The skeleton of 10-μm mesh size was 3D-printed by two-photon polymerization (2PP) lithography out of photoresist. By taking advantage of the 2PP technique's ability to selectively solidify photosensitive material within the very small focal spot of the laser, the authors achieved precise, local control of the lattice structure at a resolution as high as 100 nm (Fig. 1b). By pixel-by-pixel mapping of 10,000 square meta-lattices with different laser scanning powers, the grayscale values of the designed pattern were converted into corresponding pixels with different reconfigurability, resulting from a plethora of cross-sectional geometries. To ensure uniform contraction of the muscle material across the micrometre-size lattice to the millimetre-size canvas with adequate optical transmittance, the classic thermoresponsive hydrogel poly(*N*-isopropylacrylamide) was modified by incorporating hydrophilic monomers. Thus, as temperature increased, the soft hydrogel muscle underwent uniform thermal shrinkage while maintaining excellent optical transparency, causing its embedded lattice to buckle, where each localized lattice beam formed different sinusoidal curves. The degree of buckling or the specific curve shape is determined by the rigidity of the lattice, tunable by the printing parameters (Fig. 1a). Consequently, these small lattices, sharing the same initial lattice length, can dynamically reconfigure into a range of morphologies, causing a global grayscale pattern to appear. As a proof of concept, the authors encoded and mapped grayscale information from the *Mona Lisa* into 2PP fabrication parameters. After thermally triggered reconfiguration, the thousands of small metalattices effectively depict various details of the painting. At lower temperatures, the image information remains fully encrypted as a blank square.

This work by Zhang and colleagues establishes a universal principle for creating thermoresponsive metamaterial systems with remarkable programmability. Through the precise design of each local lattice within the metastructure, a spatially homogeneous stimulus can induce diverse configurations at both the local and global levels. The next frontier in this research could be the encoding of multiple images into a single material. By strategically aligning and interleaving two or more images or patterns on a single metastructure, distinct graphic information may be displayed alternately as the viewer changes their viewing angle, creating a dynamic visual experience similar to the unique kinetic art, agamograph. Alternatively, by programming the responsiveness and deformation behaviours of the material across varying temperatures, a series of patterns can be displayed sequentially under different conditions. A seemingly ordinary canvas may dynamically transform into any artistic masterpiece one can envision. This continuous display can further advance the broad fields of encryption, smart lenses and glasses, and augmented-reality technology.

Zixiao Liu & Ximin He
Department of Materials Science and Engineering, University of California Los Angeles, Los Angeles, CA, USA.
e-mail: ximinhe@ucla.edu

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Competing interests

The authors declare no competing interests.