Fabrication of Highly Stretchable Serpentine Structures

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Introduction

A magnetically actuated soft robot can grasp organoids to get electrophysiological data and holds promising potential for applications such as drug delivery, targeted therapy, and biopsy. In previous studies, soft-robots were designed solely for gripping without an arm structure. However, by incorporating a highly stretchable arm structure that can move freely under a magnetic field, it would be possible to better capture organoids in constrained environments. This device features a long, flexible arm combined with a six-petal gripper, with SU8 as its primary material. For efficient motion and optimal performance, precise photolithographic patterning and careful control of SU8 thickness are essential.

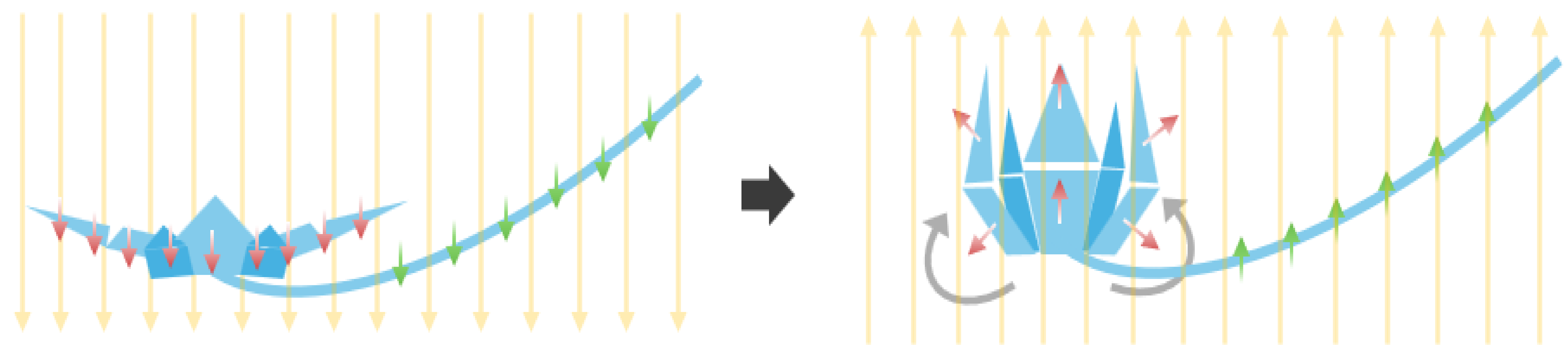
In this study, we designed and evaluated five distinct arm structures to enhance the soft robot's mobility and conducted experiments to determine which configuration yields the most effective movement. Furthermore, we varied the SU8 thickness to examine how changes in material parameters affect the device's fabrication.

Main Idea

Magnetism

Arm – Ferromagnetic MNP Printing

Gripper – Superparamagnetic MNP Printing

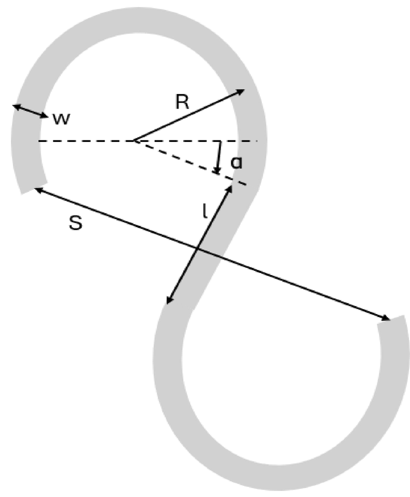


The ferromagnetic arm, with high coercivity, maintains its internal magnetization direction even when the external magnetic field changes, generating torque for gripping.

In contrast, the superparamagnetic arm continuously aligns its internal magnetization with the external field, enabling navigation movements.

Stretchability

Analytical analysis was conducted on serpentine structures considering geometric parameters such as ribbon width, arc radius, arm length, and so on. A unit cell is a part of a one-directional periodic serpentine ribbon, and its stretchability was expressed using the following equation:
(Thomas Widlund et al., "International Journal of Solids and Structures", *ELSEVIER*, 2014, 51, 4026-4037)



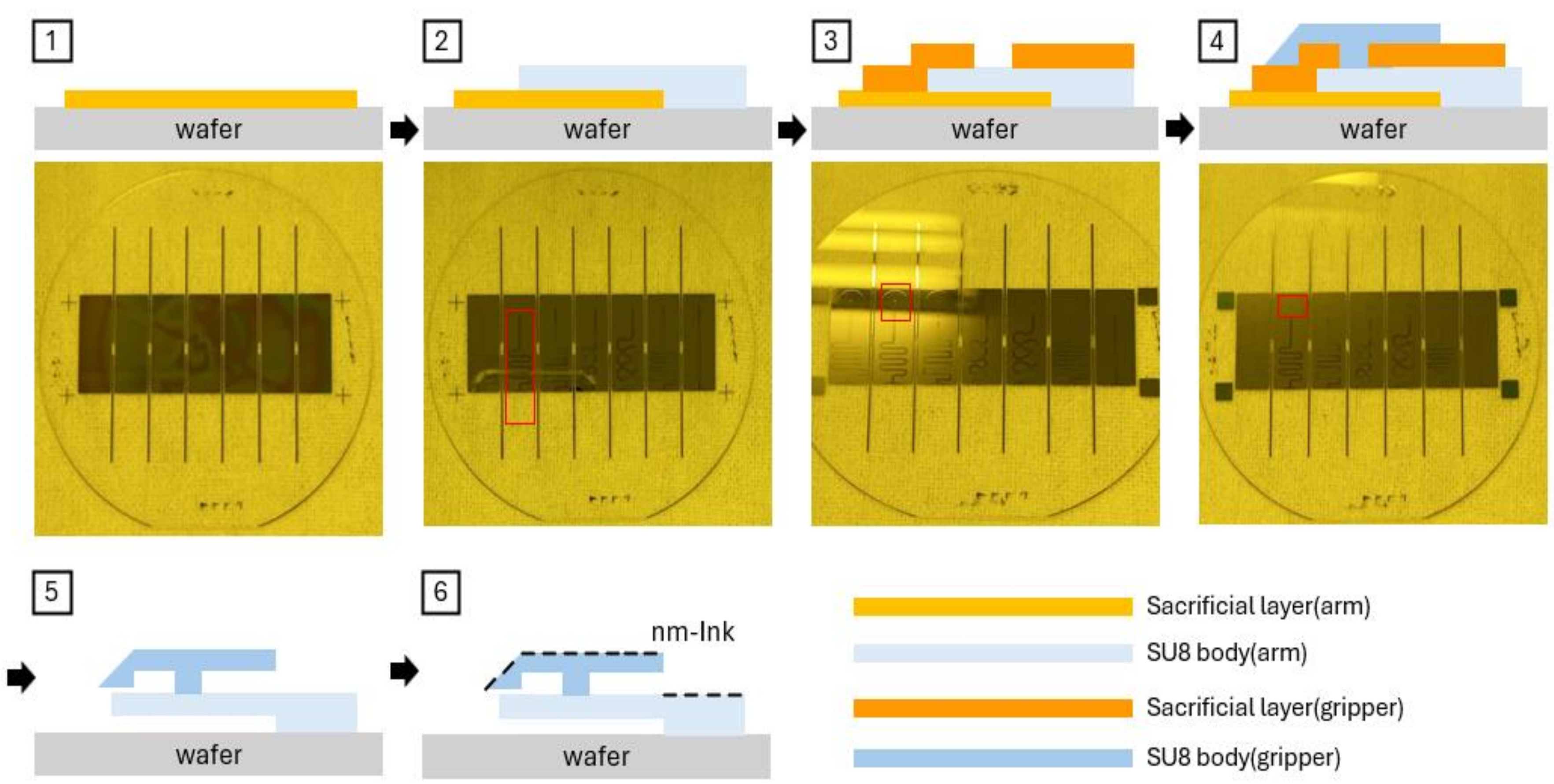
$$stretchability = \varepsilon_{app}^{cr} = \frac{\varepsilon_{cr}}{\frac{\varepsilon_{max}}{\varepsilon_{app}}}, \quad \bar{E} = \frac{E}{1-\nu^2} \quad \frac{\varepsilon_{max}}{\varepsilon_{app}} = f(\alpha, \frac{w}{R}, \frac{l}{R})$$

$$\frac{\varepsilon_{max}}{\varepsilon_{app}} = \frac{\frac{w}{R}[\frac{12}{2-\frac{w}{R}} + (\frac{12}{2-\frac{w}{R}} - \frac{w}{R})(\sin\alpha + \frac{l}{2R}\cos\alpha)]\,(\cos\alpha - \frac{l}{2R}\sin\alpha)}{[cos^2\alpha\left(\frac{l^3}{2R^3} + 3\left(\frac{\pi}{2}+\alpha\right)\frac{l^2}{R^2} + 12\frac{l}{R} - 12\left(\frac{\pi}{2}+\alpha\right)\right) + sin2\alpha(6\left(\frac{\pi}{2}+\alpha\right)\frac{l}{R}+9) + \frac{w^2}{R}[\left(\frac{\pi}{2}+\alpha\right)(\frac{l}{2R}cos\alpha + sin\alpha)^2 + \frac{l}{2R}(sin\alpha + \frac{3\bar{E}}{2G}cos\alpha)] + 18\left(\frac{\pi}{2}+\alpha\right)]}$$

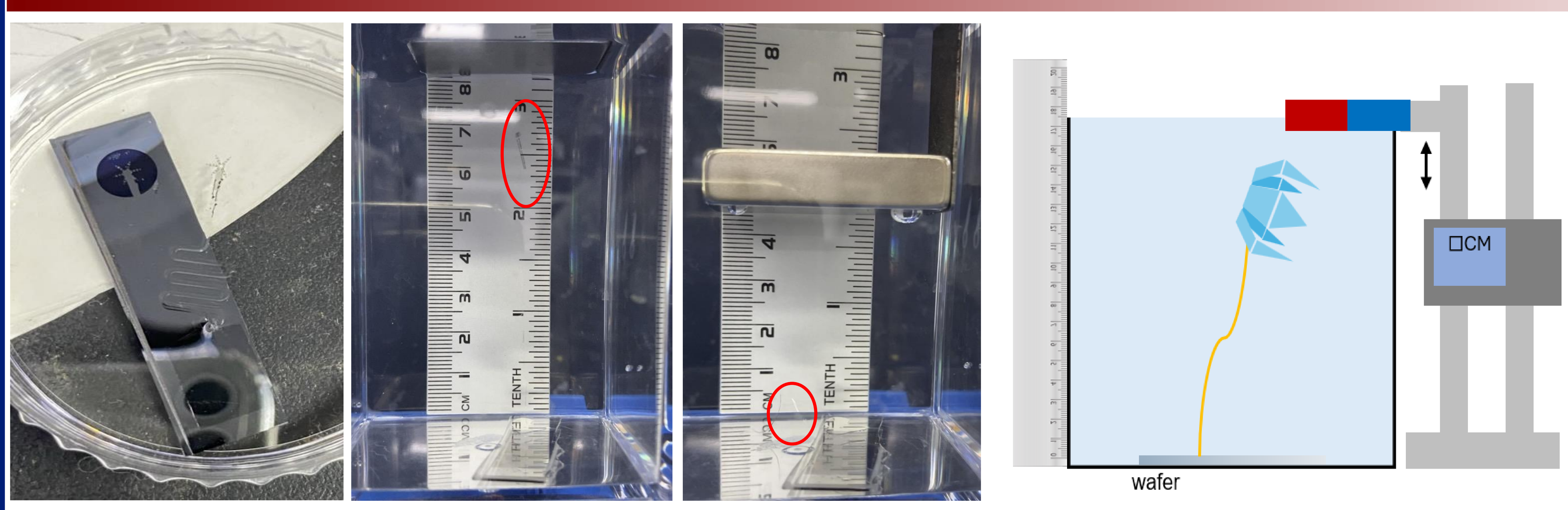
The shear modulus G of SU8 was assumed to be 0.82GPa, the Poisson's ratio ν was set to 0.22, and although the Young's modulus E of SU8 ranges from 0.9 to 7.4GPa, it was assumed to be 2GPa for this analysis.

Experimental Methods

Fabrication



Measurment



The stretchability of six different arm structures was evaluated.

Gripper

– SU8 6000.5 4000rpm × 1 / 6000.5 1500rpm × 2 (~1.4um)

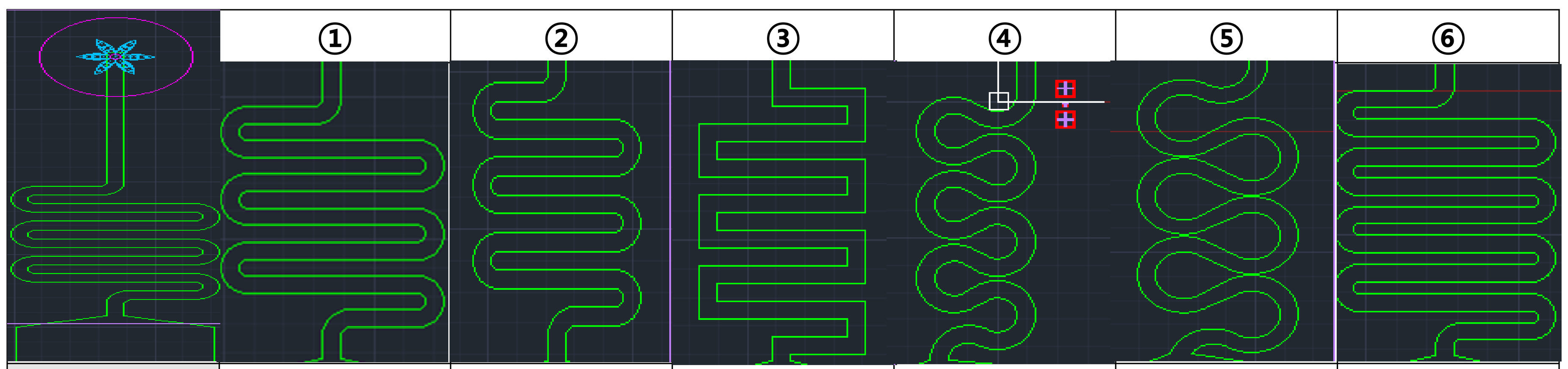
Arm

Case1) SU8 6002 4000rpm × 1 / 6000.5 1500rpm × 2 (~2.9um)

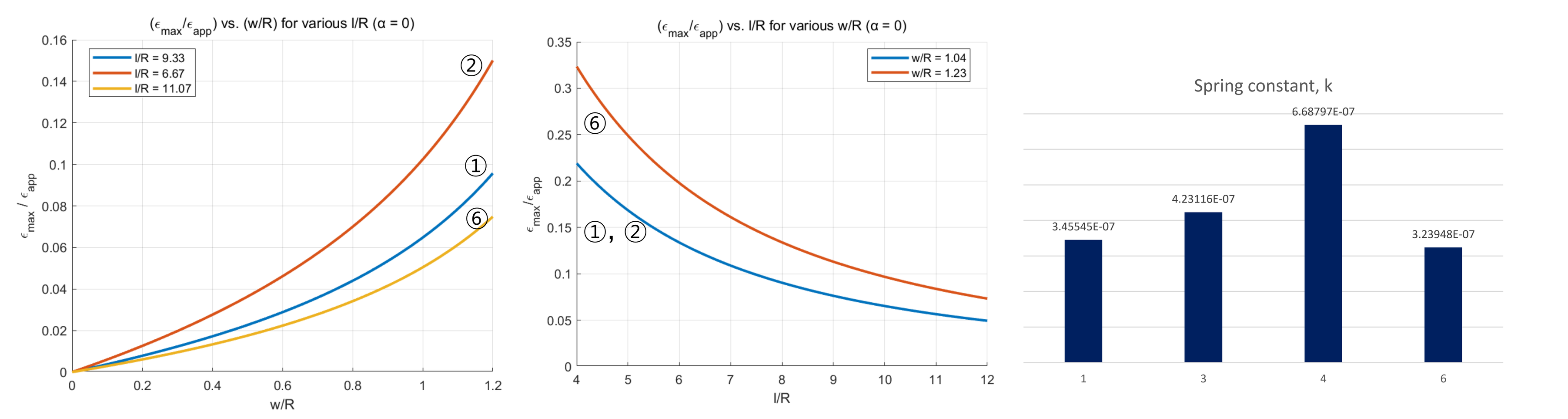
Case2) SU8 6002 4000rpm × 2 (~3.6um)

$magnetic\ force\ F\ [N] = m\ [emu] \cdot \nabla B\ [T/m],\ hooke's\ law\ F = kx$, k = spring constant

Results



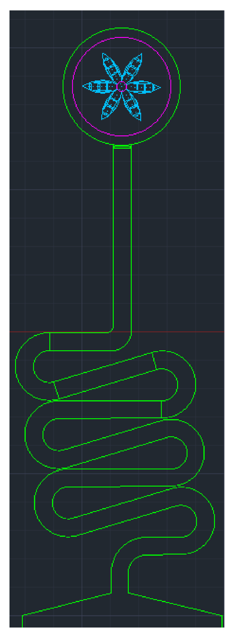
	①	②	③	④	⑤	⑥
α(radian)	0	0	-	0.5236, 30°	0.5236, 30°	0
w/R	1.037	1.037	-	0.4825	0.4825	1.229
l/R	9.333	6.667	-	0.5920	0.9310	11.07
$\varepsilon_{max}/\varepsilon_{app}$	0.002	0.0023	-	0.0035	0.0022	0.0023
$k_{experimental}$	3.46e-7	-	4.23e-7	6.69e-7	-	3.24e-7



When the arm thickness (~2.9 µm) was thin, it frequently broke during lift-off. To address this, the thickness was increased to 3.6 µm, which significantly improved durability. However, if the arm becomes too thick, the petals of the gripper tend to detach more easily.

Another issue is that, in PBS instead of DIW, the device does not settle well, and air bubbles are trapped at the bent sections or around the gripper.

Conclusion & Further Study



The magnetic force F was determined using the moment and gradient B and set to 2.07327e−6. Comparing the analytical and experimental results, structure ④ exhibited the lowest stretchability, while structures ① and ⑥ demonstrated the highest stretchability.

X = $\left(R - \frac{w}{2}\right) cos\alpha - lsin\alpha - \left(R + \frac{W}{2}\right)(1 - cos\alpha) = 0$

Y = $2R + w + 2Rsin\alpha + lcos\alpha = 10w$

The minimum value of $\varepsilon_{max}/\varepsilon_{app}$ was calculated under the above two constraint conditions. Additionally, to address the issue of petal detachment due to height differences, the SU8 arm body was designed to be larger than the gripper.

$$\alpha = 8.7^{\circ}, \quad \frac{l}{R} = 4.12, \quad \frac{w}{R} = 0.71 \quad \frac{\varepsilon_{max}}{\varepsilon_{app}} = 0.0014$$

The petals of the gripper do not face downward, and the gripping motion is not functioning properly. This issue is expected to be improved by adjusting the gripper's structure, thickness, and curing conditions.

Research will also be conducted to address the issue of the gripper not settling properly in the PBS solution.

Reference

1. Jin, Qianru, et al. 'Untethered Single Cell Grippers for Active Biopsy", *Nano Lett*, 2020; 20(7), 5583-5390
2. Huang, Qi et al, "Shell microelectrode arrays(MEAs) for brain organoids", Science advance, 2022 18(33), eabf5031
3. Y. Zhang, et al, "Experimental and theoretical studies of serpentine microstructures bonded to prestrained elastomers for stretchable electronics", Adv.Fuct.Mater, 2014, 24(14), 2028-2037
4. Kim, Yoonho, et al, "Ferromagnetic soft continuum robots", Science robotics, 2019, 4(33), eaax7329