Soft Spiral-Shaped Microswimmers for Autonomous Swimming Control by Detecting Surrounding Environments

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In nature, most microorganisms have motility, which is essential for their survival or reproduction. To move, some microorganisms have evolved soft spiral-shaped flagella, which rotate through specialized motors. Many of these microorganisms can change the morphology of their spiral-shaped flagella to control their motility. Herein, by mimicking these flagella, spiral-shaped microswimmers are developed for various applications, such as target drug delivery, micro-object transport, and micro-fluid manipulation. In previous studies, numerous fabrication methods of spiral-shaped microswimmers are developed. However, the swimming direction and velocity are controlled only by external systems, such as magnetic fields, because the spiral body is not able to deform. Therefore, this soft spiral-shaped microswimmer for autonomous swimming control by detecting surrounding stimuli is proposed. The velocity of microswimmer largely depends on the geometry of the microswimmer’s body. Through usage of a stimuli-responsive hydrogel in the microswimmer, the geometry autonomously changes in response to the surrounding stimuli. Using finite-element simulation, it is revealed that the pattern angle is an important parameter for acceleration/deceleration of the microswimmer. The dimensionless velocity of the fabricated bilayered spiral swimmer changes by deforming the geometry in response to the surrounding thermal stimuli.

One of the most important characteristics of evolution has been motility, which became essential for survival or targeting activities like reproduction for many organisms. To this end, many microorganisms developed soft spiral-shaped flagella (typical helical waveform of *E. coli* diameter ≈400 nm and wavelength 2–5 μm), which are rotated through specialized motor units. The motions of soft spiral-shaped flagella in viscous environments (low Reynolds number Re < 1) effectively propel the microorganisms. Those microorganisms can change the morphology of their spiral-shaped flagella to control swimming motility (Figure 1a). The morphological change of the flagella achieves robust and adaptive chemotaxis responding to both attractants and repellents, such as nutrients, temperature, and pH. For example, *E. coli* controls its swimming velocity and direction by deforming its spiral-shaped flagella in response to chemical, mechanical, and temperature modifications. The force for deforming the flagella is on the order of a few piconewtons, and the time to change the swimming direction is typically 0.1 s. Spermatozoa change the waveforms of their soft flagella within 0.2 s by calcium bursts to change their swimming direction in the sperm activating and attracting factor (SAAF). These functions of autonomous swimming control based on morphology changes are functionally attractive for autonomous microrobots, because these swimming control systems are effective and valuable in the submicrometer scale to the submillimeter scale.

By mimicking these flagella systems, spiral-shaped microswimmers have been developed for various applications such as target drug delivery, micro-object transport, and micro-fluid manipulation. In previous research, several fabrication methods for spiral-shaped microswimmers have been reported, including self-scrolling, template-assisted electrodeposition, glancing and deposition, and direct laser printing. These microswimmers largely consist of metals and propel themselves by applied external rotational magnetic fields. However, the swimming direction and velocity can be solely controlled by external systems, because the morphology of their spiral bodies cannot be deformed. In addition, individual controls of microswimmers in the magnetic field are difficult because of the challenge of adjusting the magnetic fields locally. Therefore, autonomous swimming control, which is controllable by the surrounding environment, could pose an advantage for developing microswimmers.

In this work, we describe soft spiral-shaped microswimmers for autonomous swimming controlled by detecting stimuli in the surrounding environments (Figure 1b). Because our experimental setup uses low Reynolds numbers (Re < 1), we define our swimmers as microswimmers. The main components of...
our microswimmers are hydrogel and magnetic nanoparticles. The spiral-shaped microswimmer propels itself by rotational motion excited by magnetic fields. By patterning the stimuli-responsive hydrogel, the spiral shape changes in response to the environmental stimuli and, therefore, the swimming motility of the microswimmer as well. In this study, we analyzed the propulsion velocity dependence on the geometry of the swimmer’s body both theoretically and experimentally. Then, we demonstrated the change in propulsion velocity responding to the surrounding environment.

First, to design the microswimmer, the effects of geometric parameters on the propulsion velocity were theoretically evaluated. Microorganisms using spiral-shaped flagella for propulsion were modeled using resistive force theory at low Reynold’s numbers.\cite{6,23} Resistive force theory assigns a local drag coefficient to a cylindrical element of spiral-shaped flagella.

**Figure 1.** Soft spiral-shaped hydrogel microswimmers with autonomous swimming control. a) Swimming motility changed in response to the surrounding environments though a change in its geometry. b) The propulsion force was controlled by the geometry change. c) Parameters for the resistive force theory. d) Fabricated soft spiral-shaped microswimmers with different pitch angles. e) Schematic image of swimming conditions. f) The swimming behaviors of spiral swimmers. g) The relationship between the dimensionless velocity, $u^*$, and the pitch angle, $\alpha$. 
(Figure 1c). For steady-state motion, the externally applied force, \( F \), and torque, \( T \), must equal the drag on the spiral-shaped micro-swimmer. In a simplified 1D model, the helical motion is described only by the rotation and translation along the spiral axis

\[
\begin{bmatrix}
F \\
T
\end{bmatrix} = 
\begin{bmatrix}
a & b \\
b & c
\end{bmatrix} 
\begin{bmatrix}
u \\
\omega
\end{bmatrix}
\]

(1)

where \( u \) is the velocity, and \( \omega \) is the rotation speed. The coefficients, \( a, b, \) and \( c \), are the functions of geometric parameters and fluid viscosity. They can be modeled with the resistive force theory, resulting in

\[
a = \pi n D_{\text{spiral}} \left( \frac{\xi_b \cos^2 \alpha + \xi_n \sin^2 \alpha}{\sin \alpha} \right)
\]

(2)

\[
b = \frac{\pi n D_{\text{spiral}}^2}{2} (\xi_i - \xi_n) \cos \alpha
\]

(3)

\[
c = \frac{\pi n D_{\text{spiral}}^3}{4} (\xi_b \sin^2 \alpha + \xi_n \cos^2 \alpha)/\sin \alpha
\]

(4)

where \( \xi_b \) and \( \xi_n \) are drag coefficients along and perpendicular to the cylindrical axis, respectively. These drag coefficients for an infinitesimal cylindrical element on spiral-shaped flagella are defined by Lighthill\(^6\) as

\[
\xi_b = \frac{2\pi \eta}{\ln(\frac{2D}{\cos \alpha})}, \quad \xi_n = \frac{4\pi \eta}{\ln(\frac{0.9D}{\cos \alpha})} + 0.5
\]

(5)

where \( \eta \) is the fluid viscosity, and \( I \) is a spring index; \( I = D_{\text{spiral}}/D_{\text{gel}} \). When applying only a rotational magnetic field, the external force, \( F \), is zero. Thus, the propulsion speed is calculated as

\[
u = \frac{-b}{a} \omega
\]

(6)

According to Equation (2) and (3), the velocity, \( u \), is described as

\[
u = \frac{-\pi n D_{\text{spiral}}^2}{2} (\xi_i - \xi_n) \cos \alpha / \pi n D_{\text{spiral}} (\xi_b \cos^2 \alpha + \xi_n \sin^2 \alpha) \omega
\]

(7)

Equation (7) can be rewritten by nondimensionalization to ignore the influence of the spiral diameter, \( D_{\text{spiral}} \), and the rotation speed, \( \omega \)

\[
u^* = \frac{u}{D_{\text{spiral}} \omega} = \frac{- \left( \xi_i - \xi_n \right) \cos \alpha}{2\left( \xi_b \cos^2 \alpha + \xi_n \sin^2 \alpha \right)} = f(I, \alpha)
\]

(8)

When the spring index, \( I \), ranges from 2.8 to 5.0, the dimensionless velocity, \( u^* \), increases when the pitch angle, \( \alpha \), changes from 0 to \( \approx 40^\circ \) (Figure S1a, Supporting Information). Thereafter, the dimensionless velocity, \( u^* \), decreases until the pitch angle, \( \alpha \), reaches \( \approx 80^\circ \). Notably, the spring index, \( I \), has little influence on the dimensionless velocity, \( u^* \) (\( u^* = 0.098-0.118 \) during \( I = 2.8-5.0 \) and \( \alpha = 40^\circ \); Figure S1b, Supporting Information). Thus, we focused on only the pitch angle, \( \alpha \), which represents the degree of expansion and contraction of the spiral-shaped micro-swimmer for controlling the dimensionless velocity, \( u^* \).

Magnetic responsive spiral-shaped hydrogel swimmers (spiral swimmers) were fabricated by a buoyancy-assisted anisotropic gelation method\(^22,24\) (see the details in the Supporting Information). Magnetic nanoparticles (10.2% (w/w), particle diameter: \( \approx 10 \) nm) encapsulated in sodium alginate solution (2% (w/w)) were extruded into calcium chloride (CaCl\(_2\)) solution (1 M) at a constant flow rate of 200 \( \mu \text{L} \text{min}^{-1} \) via a bevel-tip capillary (inner diameter: 300 \( \mu \text{m} \) and the tip angle: 20°). Spiral swimmers with various pitch angles, \( \alpha = 14^\circ-42^\circ \), were successfully obtained (average \( D_{\text{gel}} = 476 \mu \text{m} \), average \( D_{\text{spiral}} = 1629 \mu \text{m} \), and typical spiral swimmers at \( \alpha = 17^\circ \) and 39° are shown in Figure 1d).

For propulsion velocity observation, the fabricated spiral swimmers were placed into a chamber surrounded with orthogonal Helmholtz coils (Figure 1e). The chamber was filled with highly viscous fluid (1 M CaCl\(_2\) + 0.75 g mL\(^{-1}\) sucrose solution and viscosity \( \eta = 12.6 \) mPa s). A rotational magnetic field (10 mT and 5 Hz) was applied to the spiral swimmer. The spiral swimmer successfully propelled itself in the viscous fluid (Figure 1f, and Movie 1, Supporting Information). The propulsion velocity, \( u \), the rotational speed, \( \omega \), and the spiral diameter, \( D_{\text{spiral}} \), were measured. The experimentally determined dimensionless velocity, \( u^* \), was calculated using these measured values and Equation (8). The dimensionless velocity, \( u^* \), for 12 different swimmers with \( \alpha = 14^\circ-42^\circ \) increased with increasing the pitch angle, \( \alpha \) (minimum \( u^* = 0.026 \) and maximum \( u^* = 0.077 \); Figure 1g, dot plots). This increasing tendency was similar to the theoretically calculated dimensionless velocity, \( u^* \), derived from the geometry of the swimmer (pitch angle, \( \alpha \), and spring index, \( I \)) (Figure 1g, solid line). The experimentally calculated dimensionless velocity, \( u^* \), was smaller than the theoretically derived dimensionless velocity, \( u^* \). It is considered that the resistive force theory is true only for \( \text{Re} = 0 \) (experimental conditions: \( \text{Re} = 0.051-0.162 \)), and small inertial effects still occur depending on the size and velocity of the hydrogel swimmer.\(^24\) Therefore, these results indicate that the propulsion velocity dependence on the pitch angle, \( \alpha \), was experimentally verified in our spiral swimmers.

To realize the autonomous geometry change of the spiral swimmer’s body, a stimuli-responsive hydrogel was incorporated into the spiral swimmer. Stimuli-responsive hydrogels swell and shrink in response to surrounding stimuli, such as temperature,\(^25\) pH,\(^26\) light,\(^27\) and chemical compounds.\(^28\) We adopted bilayered spiral gels\(^22\) composed of a stimuli-responsive gel and a non-responsive gel (Figure 2a). The expansion and contraction behaviors of the bilayered spiral gel depended on the cross-sectional pattern of the stimuli-responsive hydrogel.\(^22\) To design the dimensionless velocity, \( u^* \), of our bilayered spiral swimmer, a finite-element simulation was conducted. In this calculation, swell and shrink behaviors of the stimuli-responsive hydrogel were simplified as an object deformation caused by thermal shrinkage. The gel diameter, \( D_{\text{gel}} \), spiral diameter, \( D_{\text{spiral}} \), and initial pitch angle, \( \alpha_i \), were determined on the basis of the typical shape identified in the previous research\(^22\) (\( D_{\text{gel}} = 300 \mu \text{m} \), \( D_{\text{spiral}} = 1050 \mu \text{m} \), and \( \alpha_i = 20^\circ \); Figure 2b). Physical parameters of the stimuli-responsive hydrogel and non-responsive hydrogel for our calculation are summarized in Table 1 (determination of these parameters are described in the Supporting Information). Three types of bilayered spiral swimmer models were built with different pattern
angles $\theta = 0^\circ$ (inside pattern), $90^\circ$ (vertical pattern), and $180^\circ$ (outside pattern), as shown in Figure 2c.

The influence of the pattern angle, $\theta$, on the deformation was investigated by the deformation simulation of these bilayered spiral swimmer models. At $\theta = 0^\circ$, the inside pattern spiral swimmer was compressed (Figure 2d, left). On the other hand, the outside pattern spiral swimmer ($\theta = 180^\circ$) expanded (Figure 2d, right). These results show that the direction of deformation depends on the pattern angle, $\theta$.

Next, the results of deformation simulation were analyzed toward the deformation direction and the amount of deformation. We evaluated the gap of the spiral, $G = p - D_{gel}$ (Figure 2e, inset), because the deformable range of the bilayered spiral swimmer is limited by the gap $G$. The spiral swimmer was completely packed and not contracted further when the gap $G = 0$. Initially, the gap $G$ before deformation was $304 \mu m$ (Figure 2e, white bar). After the stimulus, the inside pattern spiral swimmer ($\theta = 0^\circ$ and $G = 36 \mu m$; Figure 2e, red bar) and the vertical pattern spiral swimmer ($\theta = 90^\circ$ and $G = 96 \mu m$; Figure 2e, green bar) contracted, whereas the outside pattern spiral swimmer ($\theta = 180^\circ$ and $G = 2641 \mu m$; Figure 2e, blue bar) expanded. The deformation amount of the outside pattern spiral swimmer ($\theta = 180^\circ$) was much larger than both of the inside pattern spiral swimmer ($\theta = 0^\circ$) and the vertical pattern spiral swimmer ($\theta = 90^\circ$). These results indicate that the deformation direction and the amount of deformation can be designed through the pattern angle, $\theta$.

Using these calculation results, the dimensionless velocity, $u^*$, was calculated by Equation (8). The initial dimensionless velocity before deformation, $u_i^*$, was 0.074 (Figure 2g, white bar). The calculated dimensionless velocities after deformation, $u_f^*$, were 0.061 ($\theta = 0^\circ$; Figure 2f, red bar), 0.065 ($\theta = 90^\circ$; Figure 2f, green bar), and 0.113 ($\theta = 180^\circ$; Figure 2f, blue bar). To clarify the propulsion velocity change before and after deformation.

### Table 1. Simulation parameters of stimuli-responsive hydrogel and non-responsive hydrogel.

| Parameters                              | Stimuli-responsive hydrogel | Non-responsive hydrogel |
|-----------------------------------------|----------------------------|-------------------------|
| Heat expansion coefficient [1/K]        | −0.385                     | 0                       |
| Young’s modulus [kPa]                   | 13.5                       | 48.3                    |
| Poisson’s ratio [-]                     | 0.25                       | 0.31                    |
the stimulus, we focused on the difference in dimensionless velocity, $\Delta u^* = u_i^* - u_o^*$. The inside pattern spiral swimmer ($\theta = 0^\circ$) and the vertical pattern spiral swimmer ($\theta = 90^\circ$) became slower ($\theta = 0^\circ$: $\Delta u^* = -0.0129$; Figure 2f, red bar, and $\theta = 90^\circ$: $\Delta u^* = -0.0086$; Figure 2f, green bar). On the other hand, only the outside pattern spiral swimmer ($\theta = 180^\circ$) became faster by the deformation ($\Delta u^* = 0.0399$; Figure 2f, blue bar). These results show that the propulsion velocity change of the bilayered spiral swimmer varied by changing the pattern angle, $\theta$.

From the simulation results, the inside pattern ($\theta = 0^\circ$) and outside pattern ($\theta = 180^\circ$) spiral swimmers were fabricated for demonstrating the propulsion velocity control. Poly(N-isopropyl acrylamide-co-acrylic acid) (p(NIPAM-co-AAc)), which responds to temperature change, was used as a stimuli-responsive component. To form these bilayered spiral swimmers, we used 6.8% (w/w) magnetic nanoparticles encapsulated in 2.6% (w/w) p(NIPAM-co-AAc) + 0.4% (w/w) NaAlg solution as a stimuli-responsive layer, and 3% (v/v) fluorescent microbeads (yellow-green fluorescent, 0.2 μm) encapsulated in 1.0% (w/w) NaAlg + 1.0% (w/w) propylene glycol alginate (PGAlg) solution as a non-responsive layer. The PGAlg was used to adjust the viscosity. Using a Y-connector created by two-photon stereolithography, a bilayered laminar flow was created in the bevel-tip capillary. By adjusting the direction of the laminar flow pattern to the bevel-tip capillary, an inside pattern spiral swimmer ($\theta = 17^\circ$ and $\alpha_i = 32^\circ$) and an outside pattern spiral swimmer ($\theta = 199^\circ$ and $\alpha_i = 21^\circ$) were fabricated (Figure 3a). By applying temperature stimuli (26–46 °C), the inside and outside pattern

![Figure 3](https://www.advancedsciencenews.com/doi/abs/10.1002/2000095)

**Figure 3.** Propulsion velocity control by detecting the surrounding environment. a) Deformation of the inside pattern spiral swimmer (left) and the outside pattern spiral swimmer (right). b) The relationship between the final pitch angle, $\alpha_f$, and the surrounding temperature. c) The swimming behaviors of the inside pattern spiral swimmer. d) The swimming behaviors of the outside pattern spiral swimmer. e) The dimensionless velocity change of the inside pattern spiral swimmer and the outside pattern spiral swimmer.
screwed swimmers gradually deformed to expand and to contract, respectively, with increasing temperature (Figure 3a, and Movies 2 and 3, Supporting Information).

To analyze the deformation of our bilayered spiral swimmer, we compared the measured final pitch angle, $\alpha_f$, with the calculated values on the basis of the simulation results. The final pitch angle of the inside pattern spiral swimmer eventually reached $24^\circ$ at $46^\circ$C, which was close to the simulation results ($\alpha_f = 22^\circ$; Figure 3b, red circles). On the other hand, the outside pattern spiral swimmer expanded (Figure 3b, blue squares). When a temperature stimulus of $46^\circ$C was applied, the final pitch angle of the outside pattern spiral swimmer was $32^\circ$, and the value was smaller than the simulation results ($\alpha_f = 51^\circ$). One of the reasons for these results is that the pattern angle of the fabricated spiral swimmer was slightly different from $\theta = 180^\circ$. These results indicate that the final pitch angle, $\alpha_f$, could be controlled by the strength of the external stimuli.

Finally, we verified the propulsion velocity change by deforming the geometry of the bilayered spiral swimmer caused by applying temperature stimuli. To observe the propulsion velocity change, fabricated bilayered spiral swimmers were placed into a chamber filled with $1 \text{ m CaCl}_2$ solution (experimental conditions: $Re = 0.095-5.37$). The rotational magnetic field (10 mT and 5 Hz) was applied to the bilayered spiral swimmers. The dimensionless velocity of the inside pattern spiral swimmer decreased from 0.054 ($\alpha_f = 32^\circ$) to 0.042 ($\alpha_f = 24^\circ$), as the geometry change was caused by the applied 0.5°C temperature stimuli (Figure 3c, e, left, and Movie 4, Supporting Information). In contrast, the dimensionless velocity of the outside spiral swimmer increased from 0.037 ($\alpha_f = 21^\circ$) to 0.061 ($\alpha_f = 32^\circ$) (Figure 3d, right, and Movie 5, Supporting Information). These acceleration and deceleration behaviors had tendencies similar to those of the simulation results (Figure 2f). The actual velocity showed a similar trend. The actual velocity of the inside pattern swimmer decreased from 424 to 257 $\mu$m s$^{-1}$, and the actual velocity of the outside pattern swimmer increases from 96 to 200 $\mu$m s$^{-1}$. Therefore, these results indicate that the propulsion velocity of spiral swimmers can be autonomously controlled by changing the geometry of the spiral swimmer in response to the surrounding stimuli.

Previous research has proposed micromachines with propulsion control implemented by changing the body geometry. The proposed machine could switch between only two different forms, the propulsion velocity only changed between two specific propulsion velocity values. One of the notable potentials of our spiral-shaped microswimmer is that the propulsion velocity is controlled by the applied stimuli, because the geometry of the spiral-shaped body gradually changes depending on the strength of the surrounding stimuli. Bilayered spiral-shaped hydrogel could be repeatedly deformed; thus, we think that the propulsion velocity could also be changed repeatedly, because the propulsion velocity change is dependent on the geometry variation. Moreover, the acceleration and deceleration behaviors of the spiral-shaped microswimmers were designed by adjusting both the pitch angle, $\alpha$, and the pattern angle, $\theta$. From the deformation theory of bimetal, the ratio of stimuli-responsive layer to non-responsive layer is also considered to affect the amount of deformation. The amount of deformation increases as the stimuli layer thickness, reaching a maximum at a ratio of about 2. Therefore, our proposed spiral-shaped microswimmers represent a significant new approach to realize autonomous propulsion velocity control. In contrast, our spiral swimmers also have limitations regarding to the scale of the swimmers. The scale of our swimmer is larger than the typical scale of microorganisms. Because spiral-shaped flagella have a strong advantage for swimming in fluid with a low Reynolds number, a scale of just about a couple micrometers for the microswimmers is preferred. The scale of the swimmer depends on the diameter of the bevel-tip capillary; thus, we considered that smaller swimmers could be fabricated using a bevel-tip capillary with a diameter in the tens of micrometers.

In conclusion, we demonstrated the soft spiral-shaped microswimmer for autonomous swimming control by detecting surrounding environments. The dimensionless velocity of the fabricated bilayered spiral swimmer was successfully changed by applying the thermal stimuli. Our bilayered spiral swimmers could be characterized using the ability to encapsulate various functional materials, including other stimuli-responsive hydrogels. Moreover, complex compartmentalization of the spiral swimmer characterized by a laminar flow inside the capillary can also contribute to the optimization of their internal structure and functionality enhancement. The proposed soft spiral-shaped microswimmer can open new avenues for various microscale biochemical applications, such as autonomous soft-robots and soft micro-probes for intricate, miniscule environment.

Experimental Section
See Supporting Information.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest
The authors declare no conflict of interest.

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autonomous robots, geometry changes, microswimmers, spiral-shaped hydrogels, swimming control
[1] E. Lauga, Annu. Rev. Fluid Mech. 2016, 48, 105.
[2] L. J. Fauci, R. Dillon, Annu. Rev. Fluid Mech. 2006, 38, 371.
[3] S. E. Spagnolie, E. Lauga, Phys. Rev. Lett. 2011, 106, 1.
[4] H. C. Berg, Annu. Rev. Biochem. 2003, 72, 19.
[5] B. Christopher, H. Winet, Annu. Rev. Fluid Mech. 1977, 9, 339.
[6] J. Lighthill, SIAM Rev. 1976, 18, 161.
[7] C. R. Calldine, J. Mol. Biol. 1978, 118, 457.
[8] E. M. Purcell, Am. J. Phys. 1977, 45, 3.
[9] D. F. Blair, Annu. Rev. Microbiol. 1995, 49, 339.
[10] N. C. Darnton, H. C. Berg, Biophys. J. 2000, 182, 2793.
[11] K. Shiba, S. A. Baba, T. Inoue, M. Yoshida, Proc. Natl. Acad. Sci. 2008, 105, 19312.
[12] K. E. Peyer, S. Tottori, F. Qiu, L. Zhang, B. J. Nelson, Chem. – A Eur. J. 2013, 19, 28.
[13] C. Hu, M. Hoop, S. Pané, B. J. Nelson, E. Siringil, X.-Z. Chen, F. Mushtaq, Appl. Mater. Today 2017, 9, 37.
[14] M. Zenobi-Wong, K. Sugihara, B. J. Nelson, L. Zhang, R. Mhanna, F. Qiu, Y. Ding, Small 2014, 10, 1953.
[15] S. Tottori, L. Zhang, F. Qiu, K. K. Krawczyk, A. Franco-Obregón, B. J. Nelson, Adv. Mater. 2012, 24, 811.
[16] K. Kobayashi, K. Ikuta, Proc. IEEE Int. Conf. on Micro Electro Mechanical Systems on Micro Electro Mechanical Systems, IEEE, Sorrento. 2009, p. 11.
[17] L. Zhang, J. J. Abbott, L. Dong, B. E. Kratochvil, D. Bell, B. J. Nelson, Appl. Phys. Lett. 2009, 94, 2007.
[18] R. Grisch, B. J. Nelson, M. A. Zeehan, K. M. Sivaraman, B. Özkale, K. E. Peyer, J. Sort, M. S. Sakar, E. Pellicer, S. Pané, Small 2013, 10, 1284.
[19] W. Gao, X. Feng, A. Pei, C. R. Kane, R. Tam, C. Hennessy, J. Wang, Nano Lett. 2014, 14, 305.
[20] B. Christopher, H. Winet, Annu. Rev. Fluid Mech. 1977, 9, 339.
[21] J. Lighthill, SIAM Rev. 1976, 18, 161.
[22] C. R. Calldine, J. Mol. Biol. 1978, 118, 457.
[23] E. M. Purcell, Am. J. Phys. 1977, 45, 3.
[24] D. F. Blair, Annu. Rev. Microbiol. 1995, 49, 489.
[25] N. C. Darnton, H. C. Berg, Biophys. J. 2000, 182, 2793.
[26] K. Shiba, S. A. Baba, T. Inoue, M. Yoshida, Proc. Natl. Acad. Sci. 2008, 105, 19312.
[27] K. E. Peyer, S. Tottori, F. Qiu, L. Zhang, B. J. Nelson, Chem. – A Eur. J. 2013, 19, 28.
[28] C. Hu, M. Hoop, S. Pané, B. J. Nelson, E. Siringil, X.-Z. Chen, F. Mushtaq, Appl. Mater. Today 2017, 9, 37.
[29] M. Zenobi-Wong, K. Sugihara, B. J. Nelson, L. Zhang, R. Mhanna, F. Qiu, Y. Ding, Small 2014, 10, 1953.
[30] S. Tottori, L. Zhang, F. Qiu, K. K. Krawczyk, A. Franco-Obregón, B. J. Nelson, Adv. Mater. 2012, 24, 811.
[31] K. Kobayashi, K. Ikuta, Proc. IEEE Int. Conf. on Micro Electro Mechanical Systems on Micro Electro Mechanical Systems, IEEE, Sorrento. 2009, p. 11.
[32] L. Zhang, J. J. Abbott, L. Dong, B. E. Kratochvil, D. Bell, B. J. Nelson, Appl. Phys. Lett. 2009, 94, 2007.
[33] R. Grisch, B. J. Nelson, M. A. Zeehan, K. M. Sivaraman, B. Özkale, K. E. Peyer, J. Sort, M. S. Sakar, E. Pellicer, S. Pané, Small 2013, 10, 1284.
[34] W. Gao, X. Feng, A. Pei, C. R. Kane, R. Tam, C. Hennessy, J. Wang, Nano Lett. 2014, 14, 305.
[35] B. Christopher, H. Winet, Annu. Rev. Fluid Mech. 1977, 9, 339.
[36] J. Lighthill, SIAM Rev. 1976, 18, 161.
[37] C. R. Calldine, J. Mol. Biol. 1978, 118, 457.
[38] E. M. Purcell, Am. J. Phys. 1977, 45, 3.
[39] D. F. Blair, Annu. Rev. Microbiol. 1995, 49, 489.
[40] N. C. Darnton, H. C. Berg, Biophys. J. 2000, 182, 2793.
[41] K. Shiba, S. A. Baba, T. Inoue, M. Yoshida, Proc. Natl. Acad. Sci. 2008, 105, 19312.
[42] K. E. Peyer, S. Tottori, F. Qiu, L. Zhang, B. J. Nelson, Chem. – A Eur. J. 2013, 19, 28.
[43] C. Hu, M. Hoop, S. Pané, B. J. Nelson, E. Siringil, X.-Z. Chen, F. Mushtaq, Appl. Mater. Today 2017, 9, 37.
[44] M. Zenobi-Wong, K. Sugihara, B. J. Nelson, L. Zhang, R. Mhanna, F. Qiu, Y. Ding, Small 2014, 10, 1953.
[45] S. Tottori, L. Zhang, F. Qiu, K. K. Krawczyk, A. Franco-Obregón, B. J. Nelson, Adv. Mater. 2012, 24, 811.
[46] K. Kobayashi, K. Ikuta, Proc. IEEE Int. Conf. on Micro Electro Mechanical Systems on Micro Electro Mechanical Systems, IEEE, Sorrento. 2009, p. 11.