Artificial cilia for microfluidics

exploring the use of a horizontally micro-structured ferromagnetic PDMS composite

graduation talk of
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Department of applied physics
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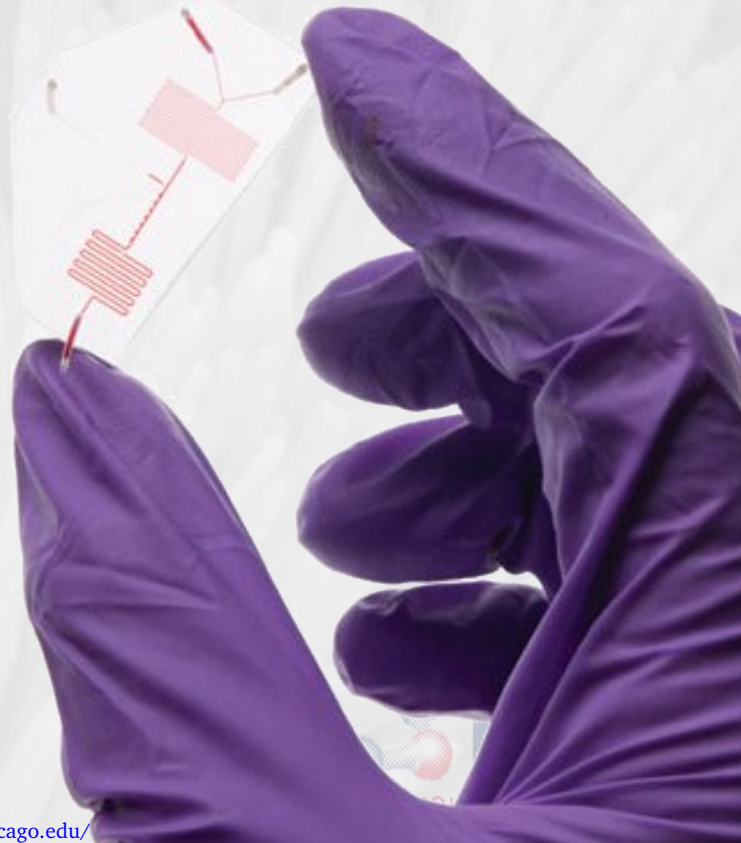
TU/e Technische Universiteit Eindhoven University of Technology

19-08-2008

DPI DUTCH POLYMER INSTITUTE

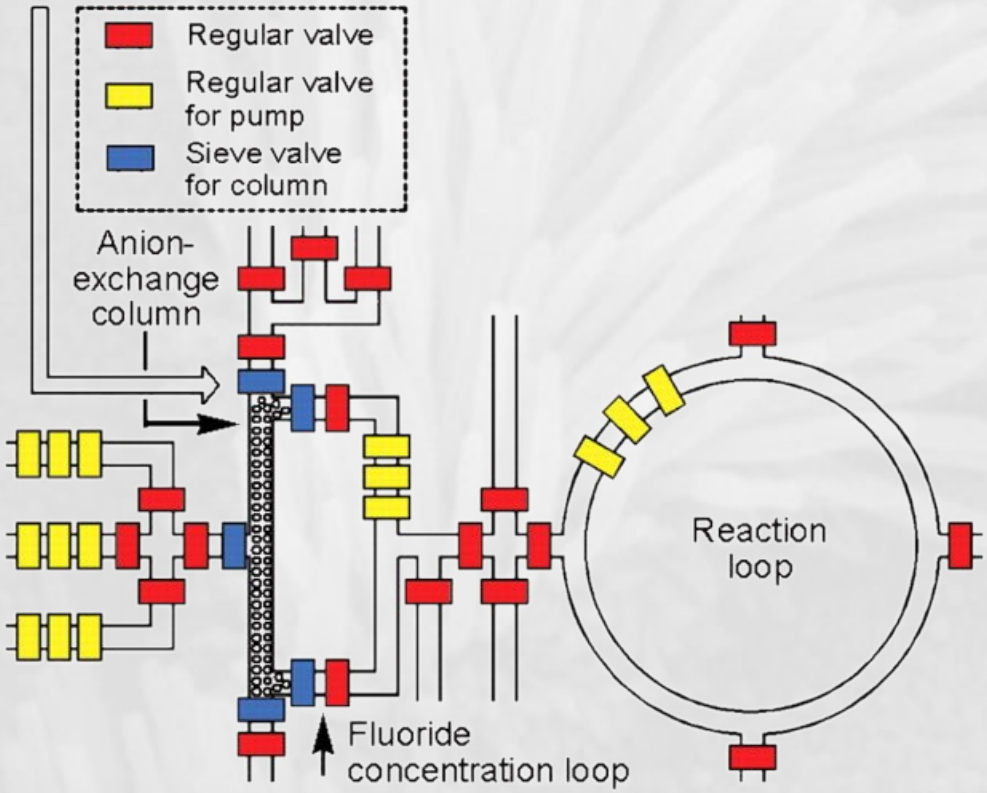
Microfluidics

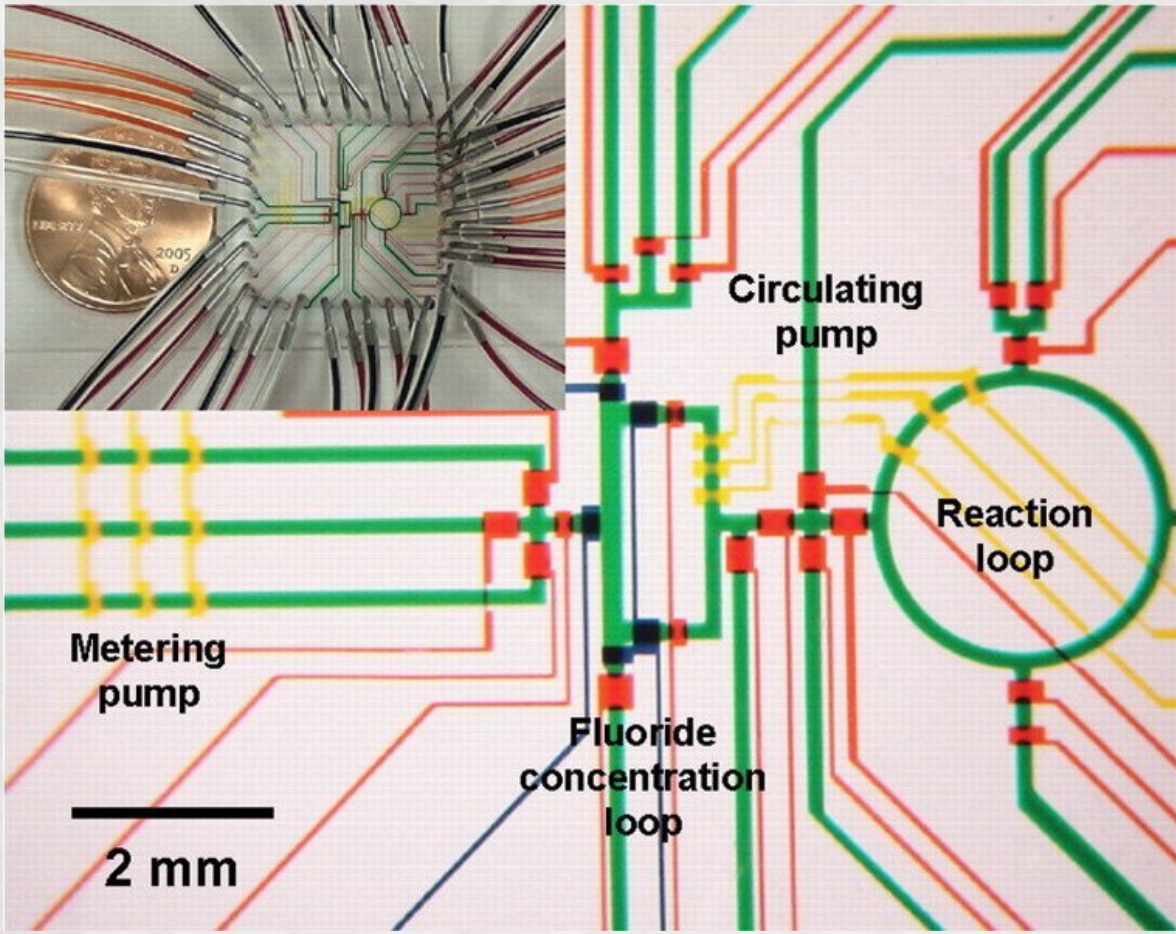
an Europa Valve plant site



http://www-news.uchicago.edu/

Microfluidic chip

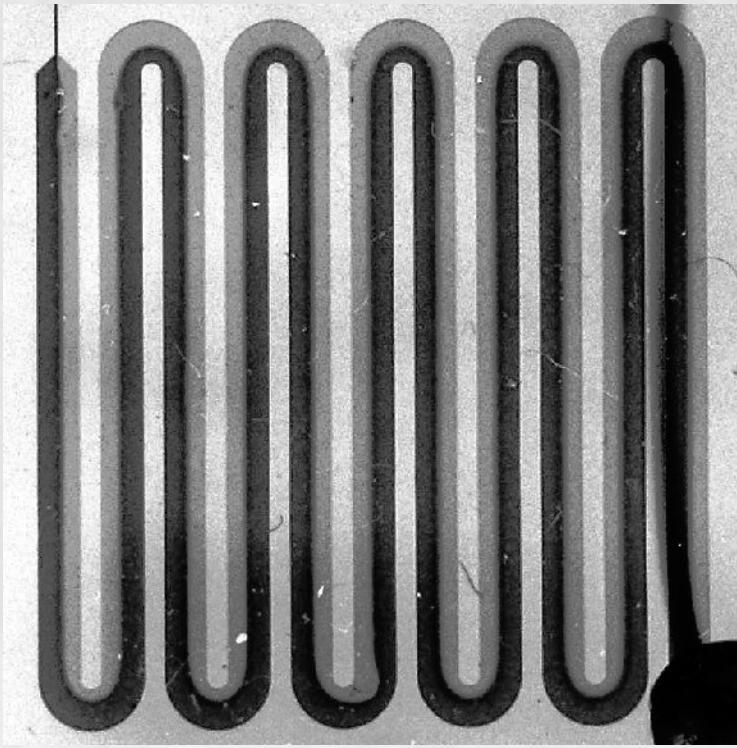




Lee et al. in Science (2005) doi:10.1126/science.1118919

Microfluidic mixing

$$Re = \frac{v_s L}{\nu} > 2300 \rightarrow turbulence$$



Green in Int. Jnl. of Multiphysics (2007)
doi:10.1260/175095407780130544

Macroscopic:

$$v_s = \frac{\nu\ Re}{L} \approx 2.3\, mm/s$$

Microscopic:

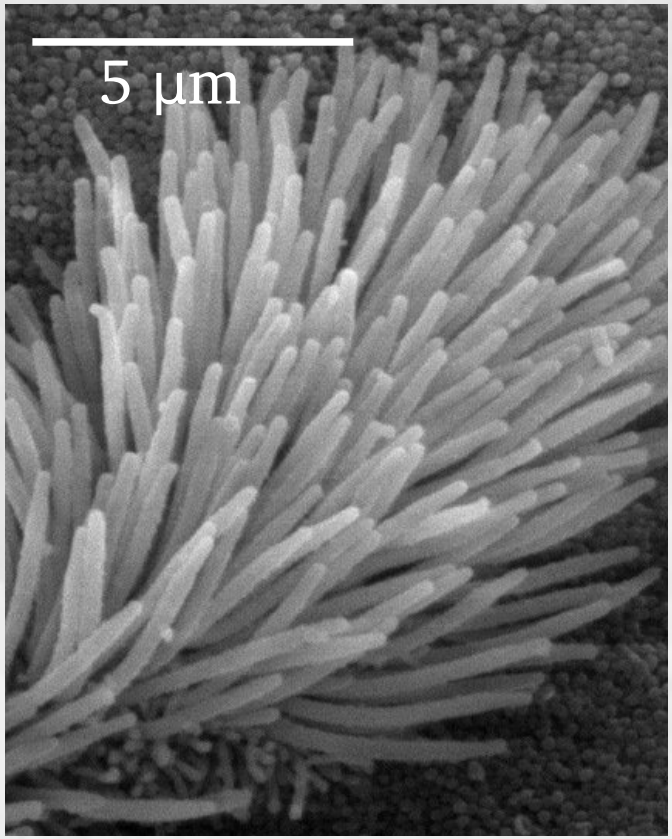
$$v_s = \frac{\nu\ Re}{L} \approx \text{۲۲}\, mm/s$$

so only mixing by diffusion

slow

Cilia in nature

Nikon MicrosopyU digital video gallery, Paramecium (protozoan)
Khatavkar et al. in Phys. Fluids (2007) doi:10.1063/1.2762206



Dartmouth Electron Microscope Facility
Mammalian lung SEM

Artificial cilia for microfluidics

Goal

→ use artificial cilia to achieve
pumping & mixing in microfluidics

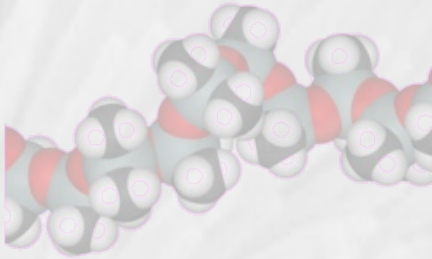
Artificial cilia for microfluidics

Goal

→ use artificial cilia to achieve
pumping & mixing in microfluidics

How?

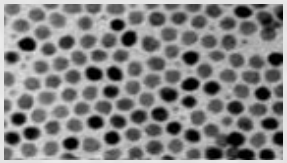
- high aspect-ratio
- polymer material
- magnetic actuation



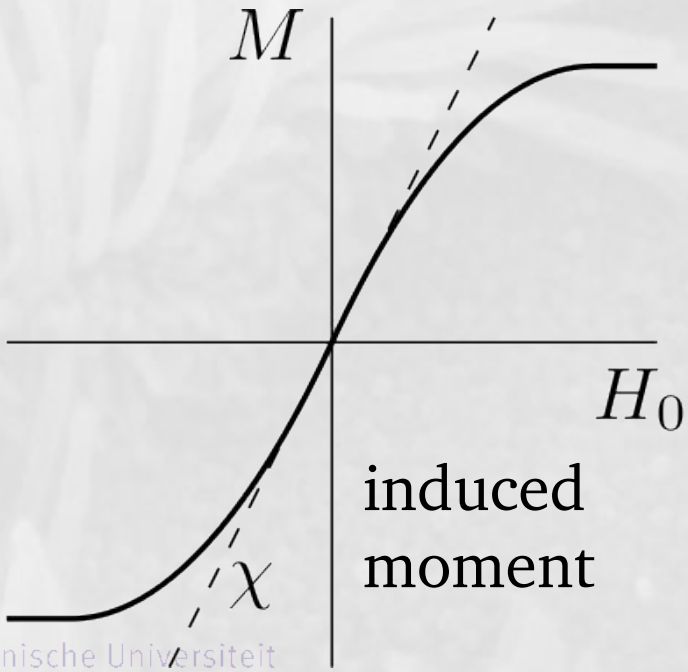
Magnetic artificial cilia

- Actuation by magnetic field
- Magnetic iron-polymer composite

Huber in Small (2005)
doi:10.1002/smll.200500006

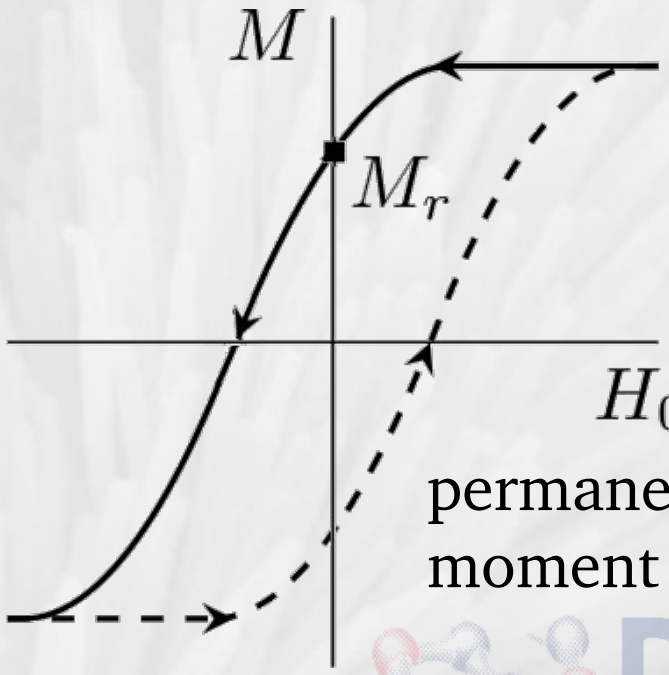


small particles (ø<20nm)
superparamagnetic



induced
moment

large particles (ø>20nm)
ferromagnetic



permanent
moment

Magnetic actuation forces

gradient force

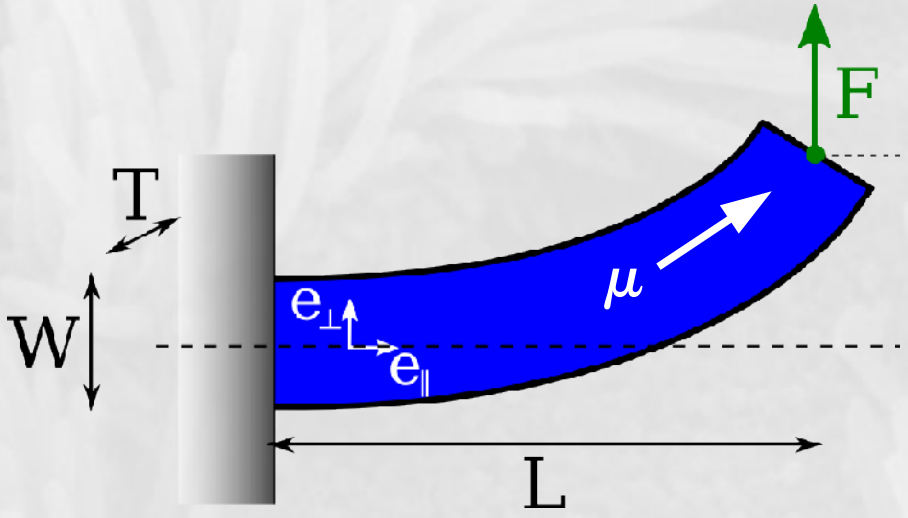
$$\vec{F}_i = \mu_0 (\vec{\mu} \cdot \nabla) \vec{H}_0$$

and

torque

$$\vec{\tau} = \mu_0 \vec{\mu} \times \vec{H}_0$$

$$\rightarrow \vec{F}_p = \frac{\mu_0}{L} (\vec{\mu} \times \vec{H}_0) \times \vec{e}_{\parallel}$$



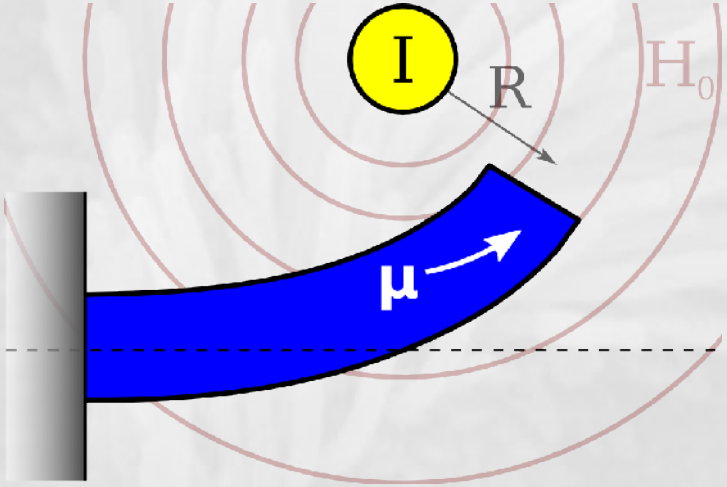
$$\delta = \frac{4 L^3 F}{E T W^3}$$

(for small deflection)

Induced versus permanent

superparamagnetic material,
induced magnetic moment

$$\vec{M} = \chi \vec{H}_0$$

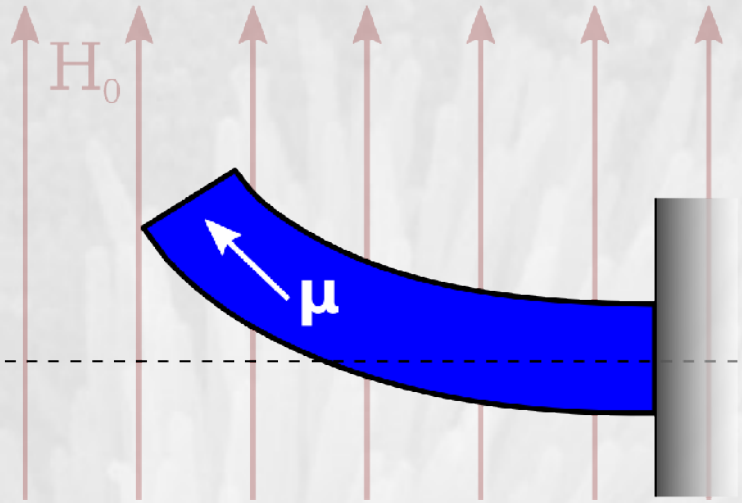


$$\vec{F}_i \propto \chi (\vec{H}_0 \cdot \nabla) \vec{H}_0, \quad \vec{\tau} \approx 0$$

$$\frac{\delta_i}{W} = \frac{\mu_0 \chi j^2}{E \pi^2} \cdot \frac{L^3 r^4}{W^2 R^3}$$

ferromagnetic material,
permanent magnetic moment

$$\vec{M} = \vec{M}_r$$



$$\vec{F}_i = 0, \quad \vec{\tau} \propto \vec{M} \times \vec{H}_0$$

$$\frac{\delta_p}{W} = \frac{4 \mu_0 M H_0}{E} \cdot \frac{L^3}{W^3}$$

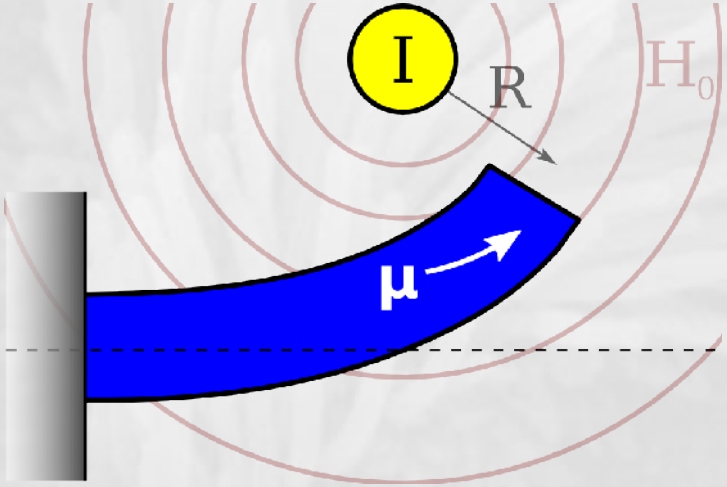
$$\vec{F}_i = \mu_0 (\vec{\mu} \cdot \nabla) \vec{H}_0$$

$$\vec{\tau} = \mu_0 \vec{\mu} \times \vec{H}_0$$

Induced versus permanent

superparamagnetic material,
induced magnetic moment

$$\vec{M} = \chi \vec{H}_0$$



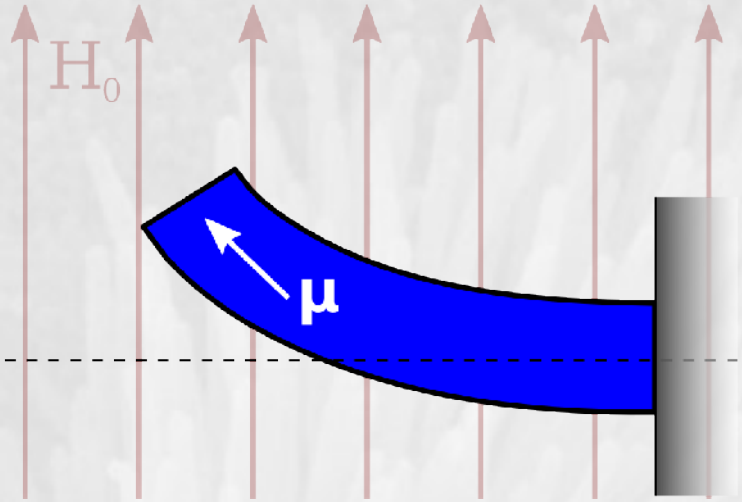
$$\vec{F}_i \propto \chi (\vec{H}_0 \cdot \nabla) \vec{H}_0, \quad \vec{\tau} \approx 0$$

$$\frac{\delta_i}{W} = \frac{\mu_0 \chi j^2}{E \pi^2} \cdot \frac{L^3 r^4}{W^2 R^3}$$

scale-dependent

ferromagnetic material,
permanent magnetic moment

$$\vec{M} = \vec{M}_r$$

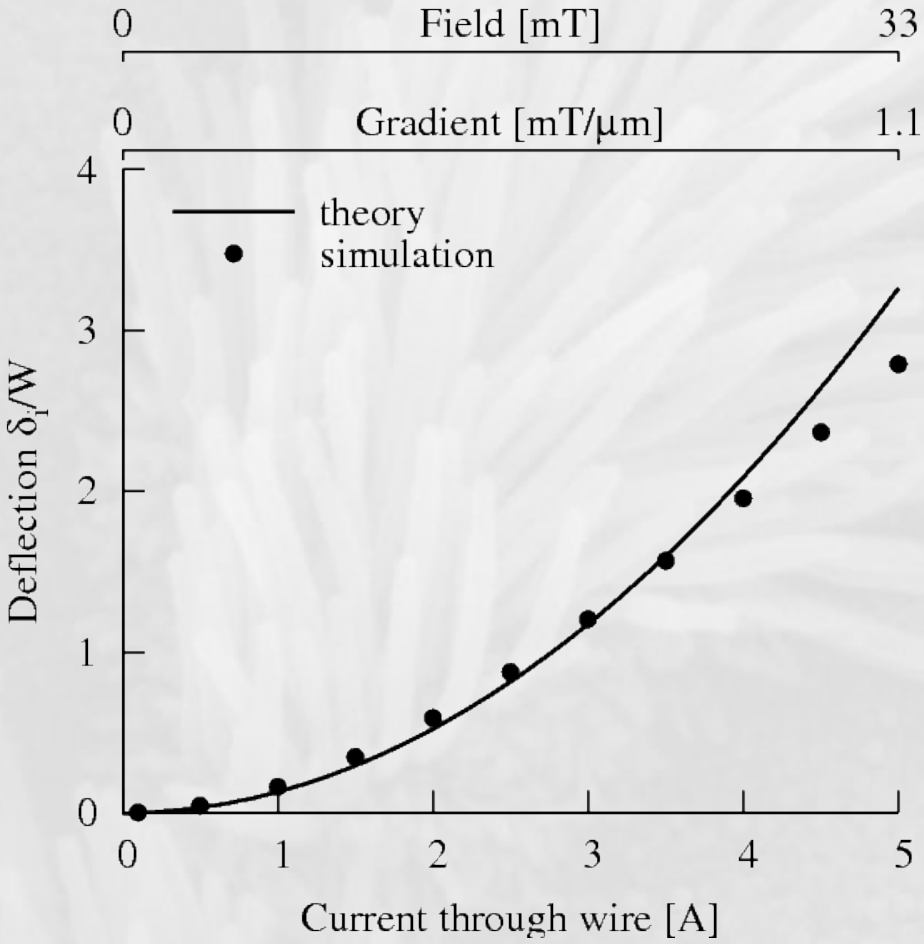


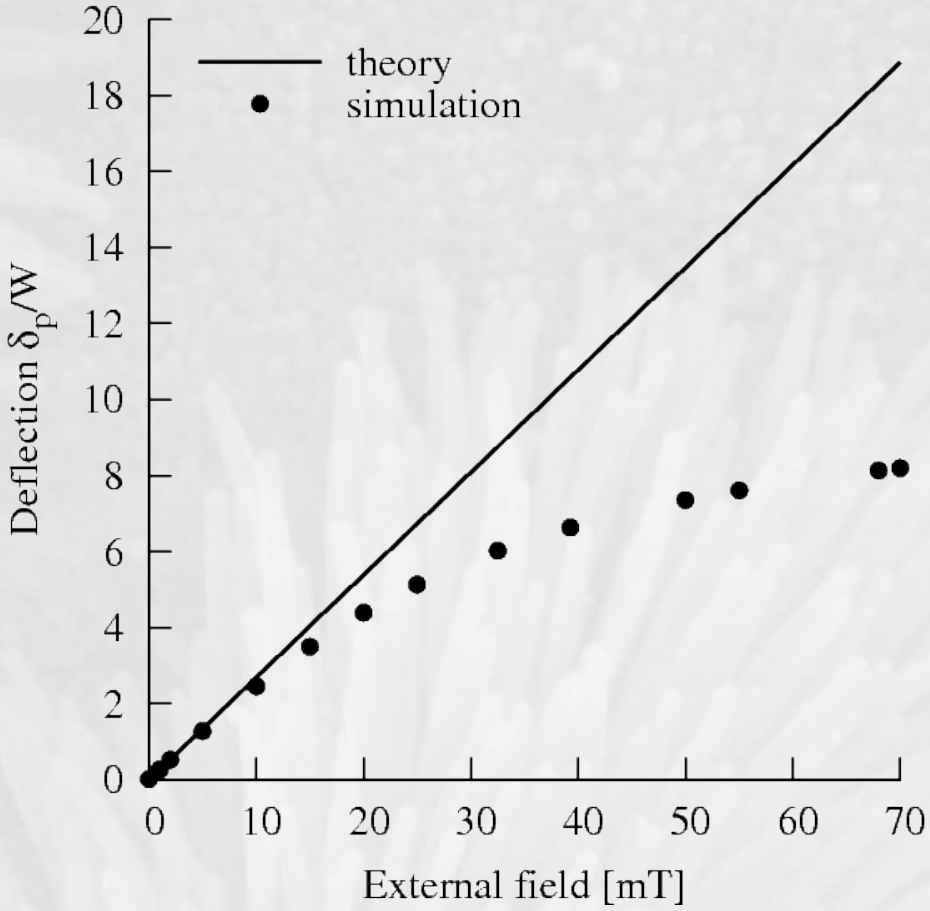
$$\vec{F}_i = 0, \quad \vec{\tau} \propto \vec{M} \times \vec{H}_0$$

$$\frac{\delta_p}{W} = \frac{4 \mu_0 M H_0}{E} \cdot \frac{L^3}{W^3}$$

scale-invariant

Validity





$$\frac{\delta_i}{W} = \frac{\mu_0 \chi j^2}{E\pi^2} \cdot \frac{L^3 r^4}{W^2 R^3}$$

$$\frac{\delta_p}{W} = \frac{4\mu_0 M H_0}{E} \cdot \frac{L^3}{W^3}$$

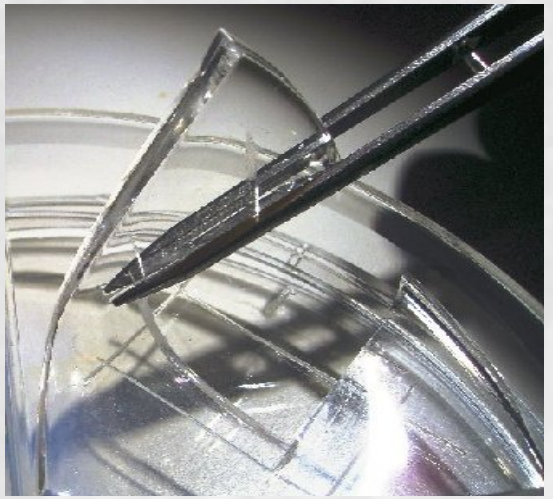
W=10μm, L=120μm

E=0.5MPa, χ=0.8, M=25mT

Large artificial cilium – fabrication

Polymer polydimethylsiloxane

(liquid)



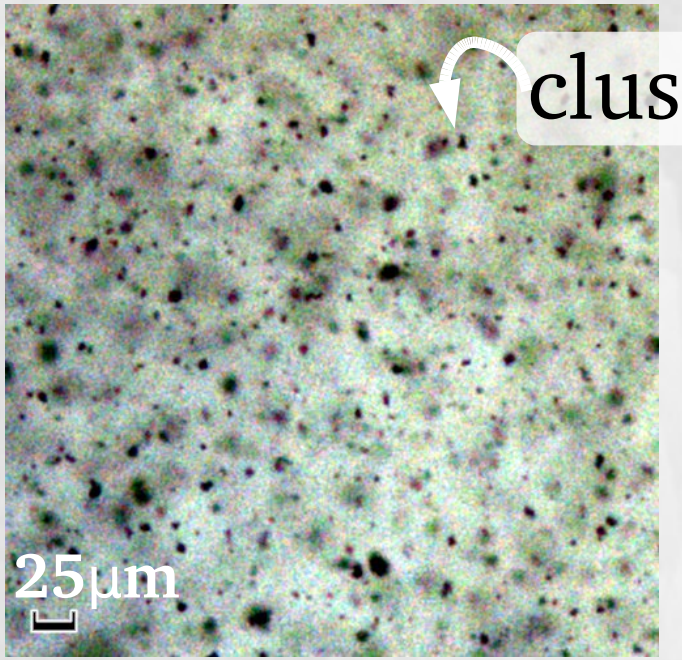
(solid silicone resin)

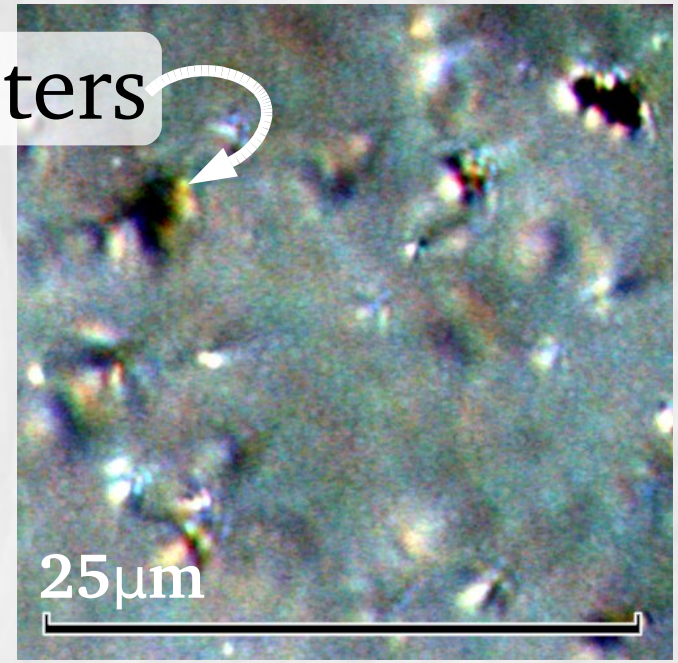
Sylgard-184

Large artificial cilium – fabrication

Polymer polydimethylsiloxane (PDMS)

... made permanently magnetic by doping with ferromagnetic particles, 70nm Fe@C



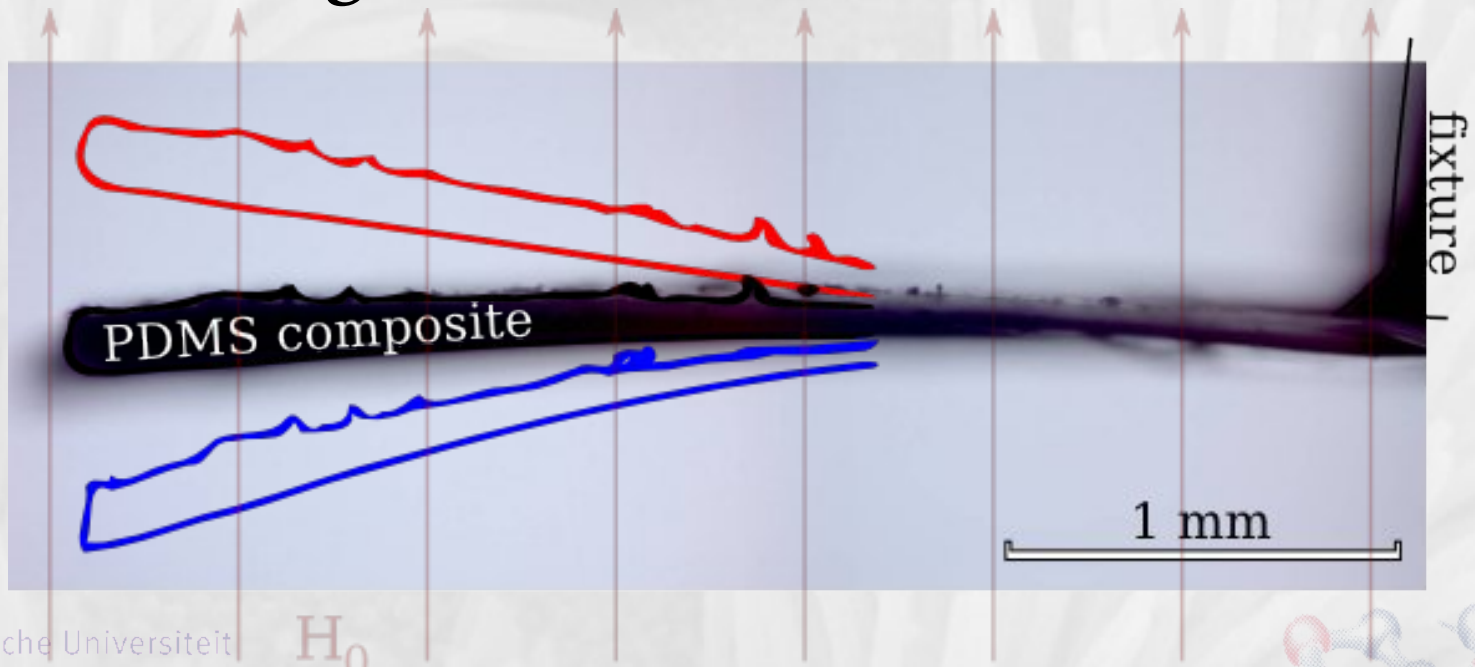


Large artificial cilium – fabrication

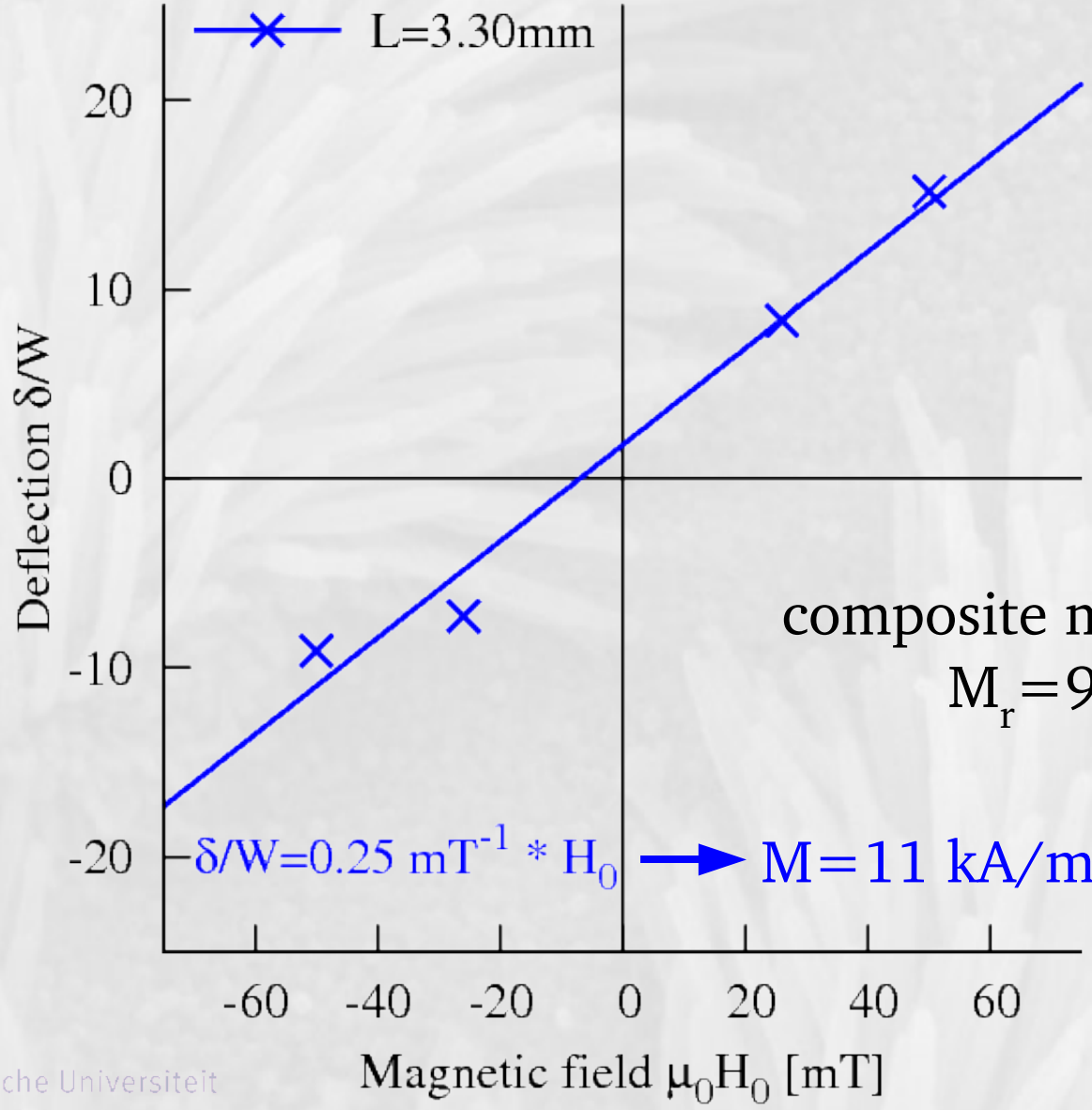
Polymer polydimethylsiloxane (PDMS)

... made permanently magnetic by doping with ferromagnetic particles, 70nm Fe@C

Cut out a rectangular slab



Large artificial cilium – response



$$\frac{\delta_p}{W} = \frac{\varepsilon \mu . L^3 M H .}{E W^3}$$

composite measurements:
$M_r = 96$ kA/m

W= 66μm, 2.2 vol% Fe@C

Micro-fabrication

High aspect-ratio for high deflection

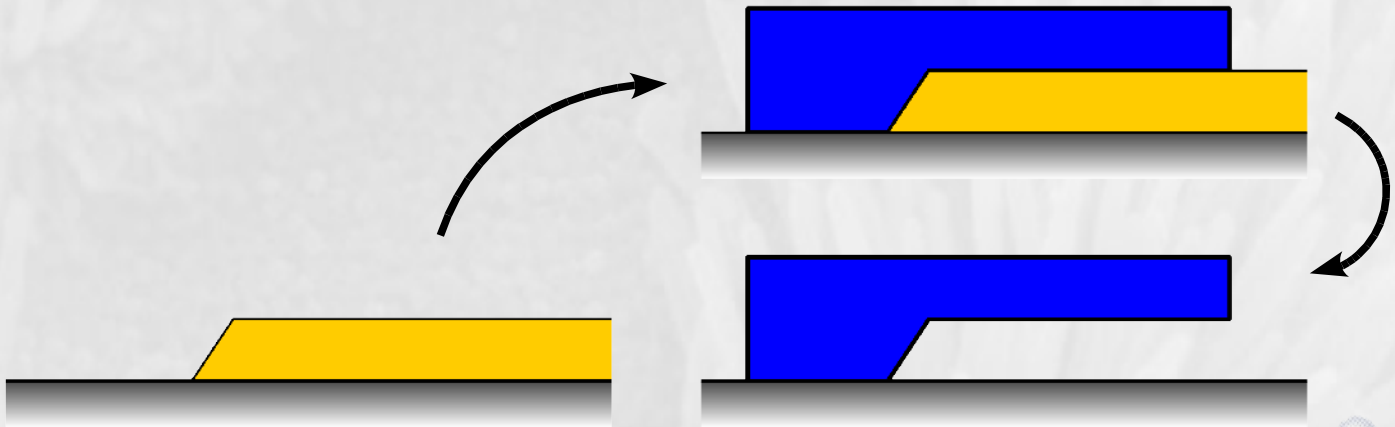
$$\frac{\delta}{W} \propto \left(\frac{L}{W}\right)^3$$

Horizontal fabrication by
sacrificial layer lift-off technique

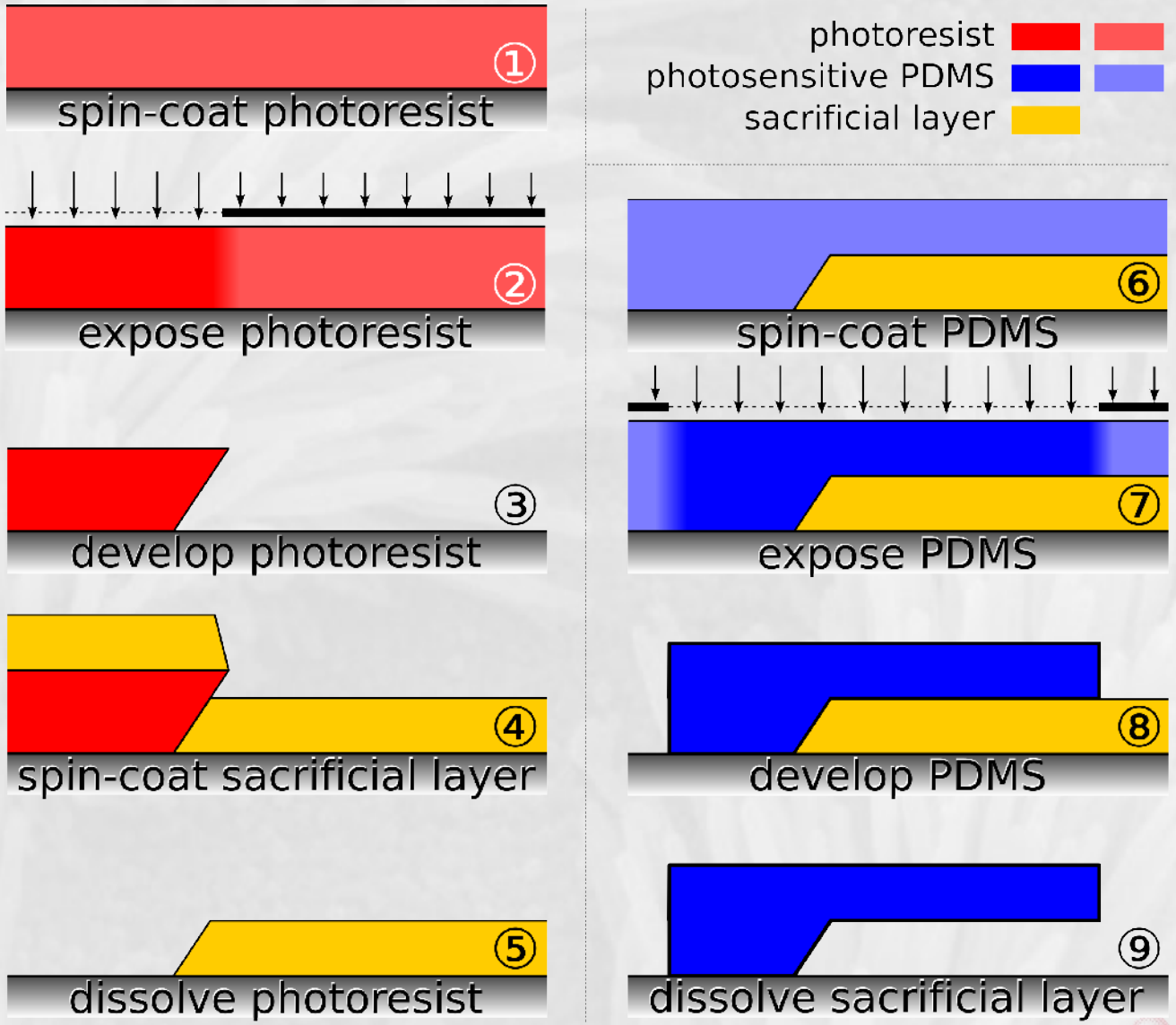
Micro-fabrication – procedure

PDMS
sacrificial layer

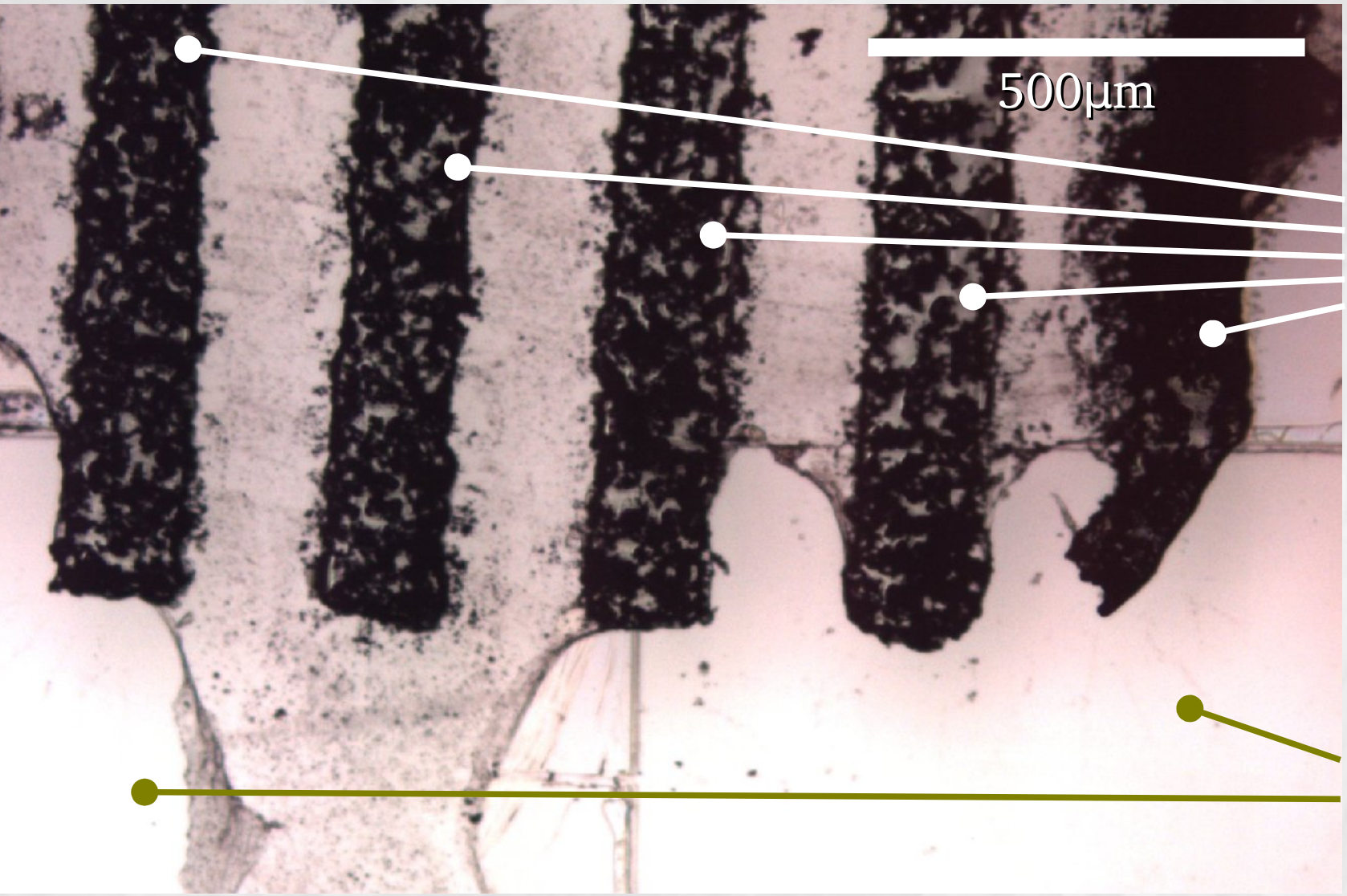
Horizontal fabrication by
sacrificial layer lift-off technique



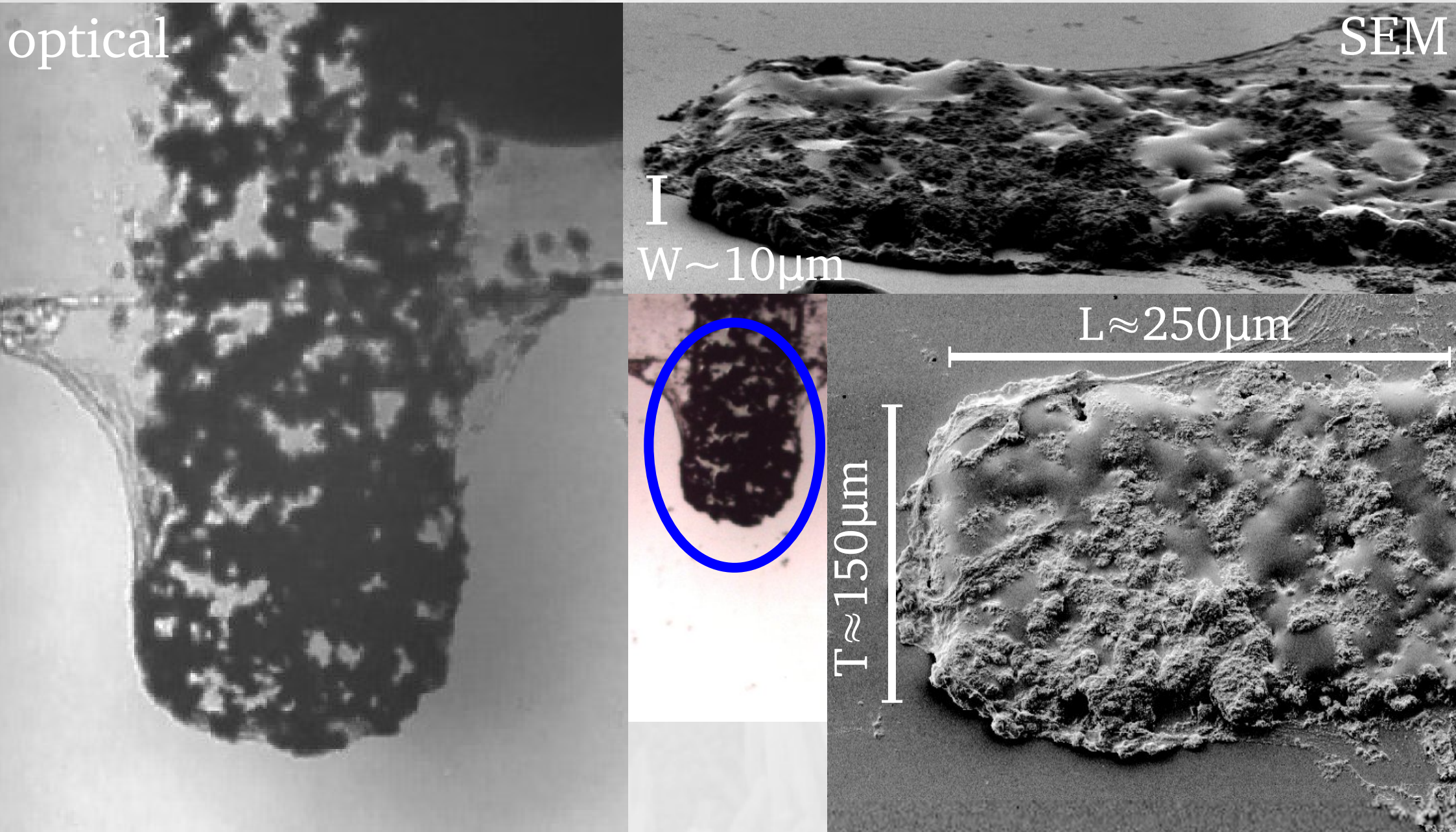
Micro-fabrication – procedure



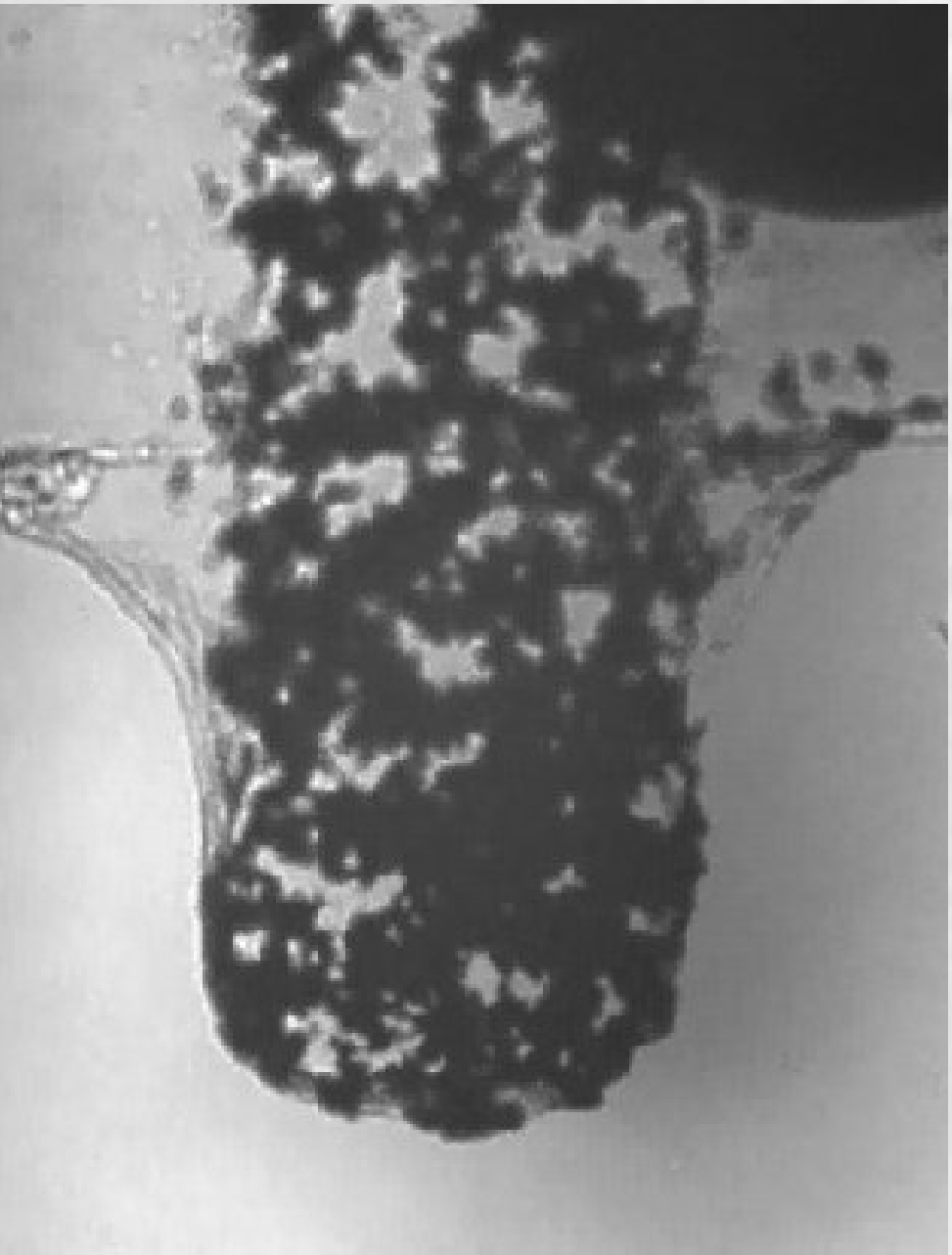
Micro-fabrication – result

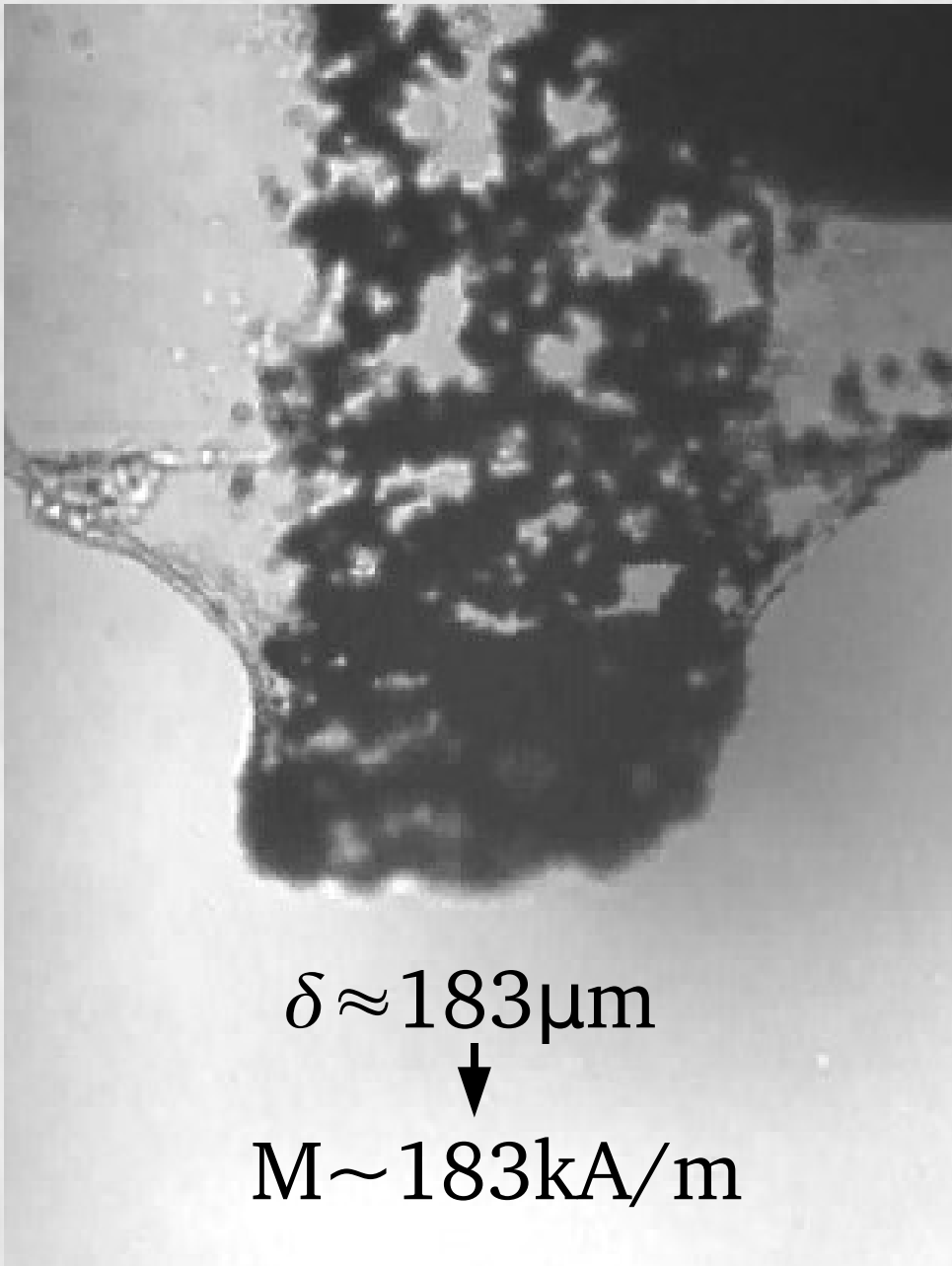


Micro-fabrication – result



Micro-fabrication – result



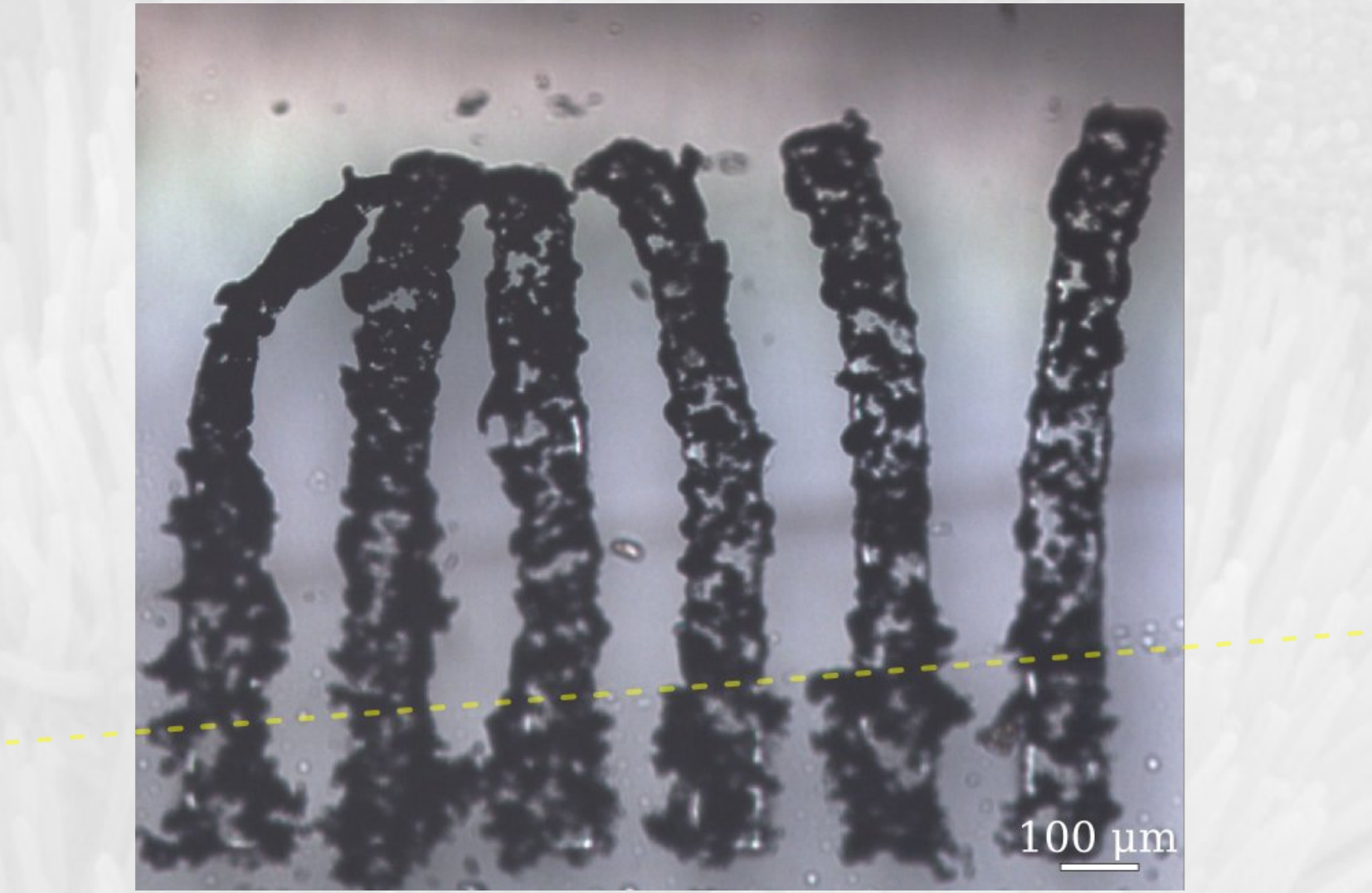


$\delta \approx 183\mu m$

↓

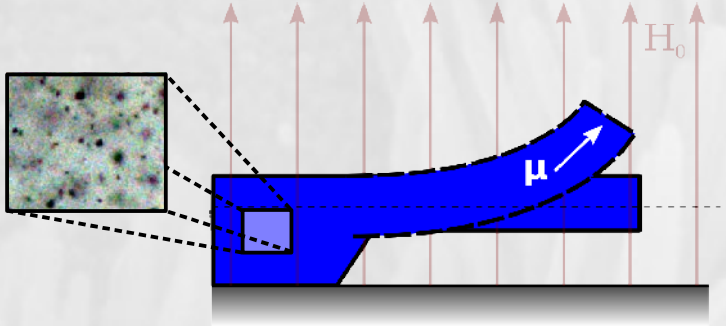
$M \sim 183 kA/m$

Micro-fabrication – long cilia



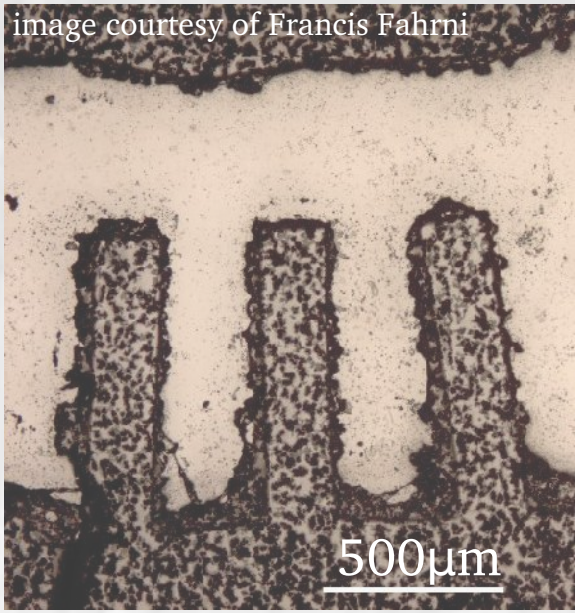
Conclusion

- Permanently magnetic artificial cilia bend in a perpendicular magnetic field
  - scaling independent
  - p^3 aspect-ratio dependence
  - perform better than cilia with induced moment
- Experiment confirms order-of-magnitude theory
- Micro-fabrication of artificial cilia was shown



Outlook

- Details of fabrication procedure
  - parameters
- Multiple cilia in a microfluidic channel
  - mask design
- Actuation for mixing and pumping



thank you for your attention