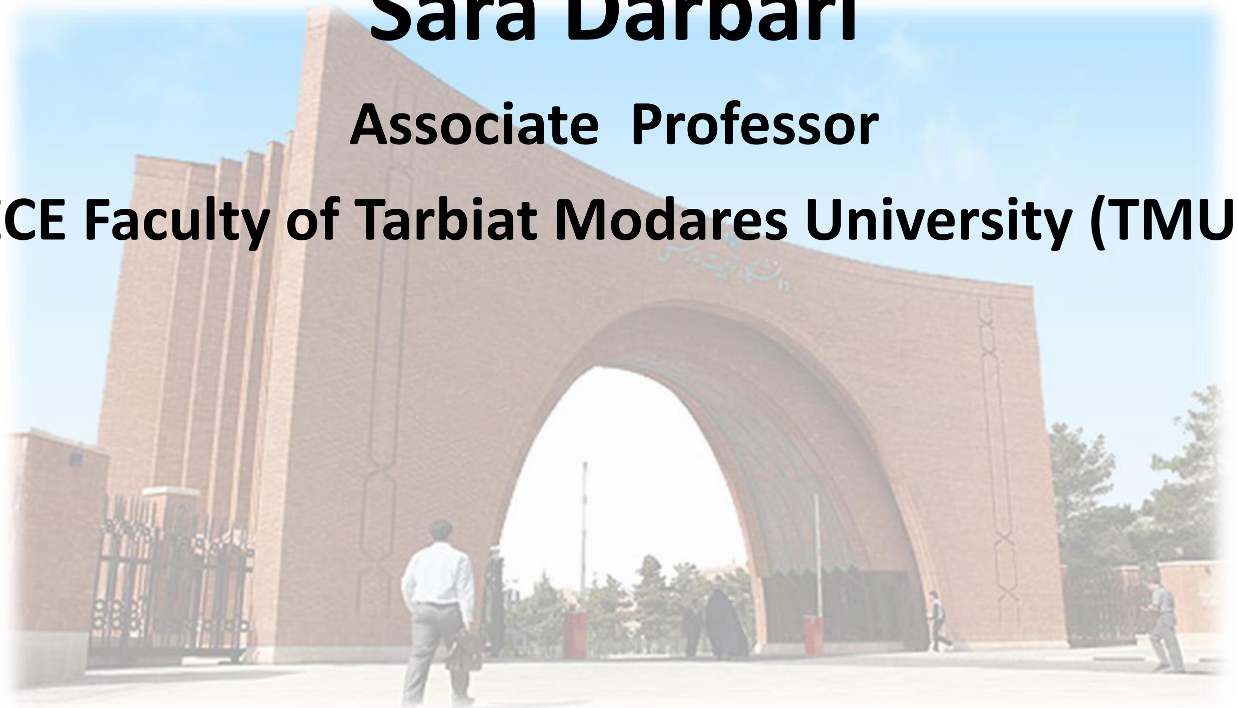
Manipulation of bio-particles by surface acoustic waves (SAWs)

Sara Darbari

Associate Professor

ECE Faculty of Tarbiat Modares University (TMU)



Faculty of Electrical and Computer Engineering

- The Faculty of Electrical and Computer Engineering (ECE), one of the oldest Faculties in TMU.

Nanosensors and Detectors Lab. (NSDL) and my research group

NSDL, founded in 2017

My research group

Outline

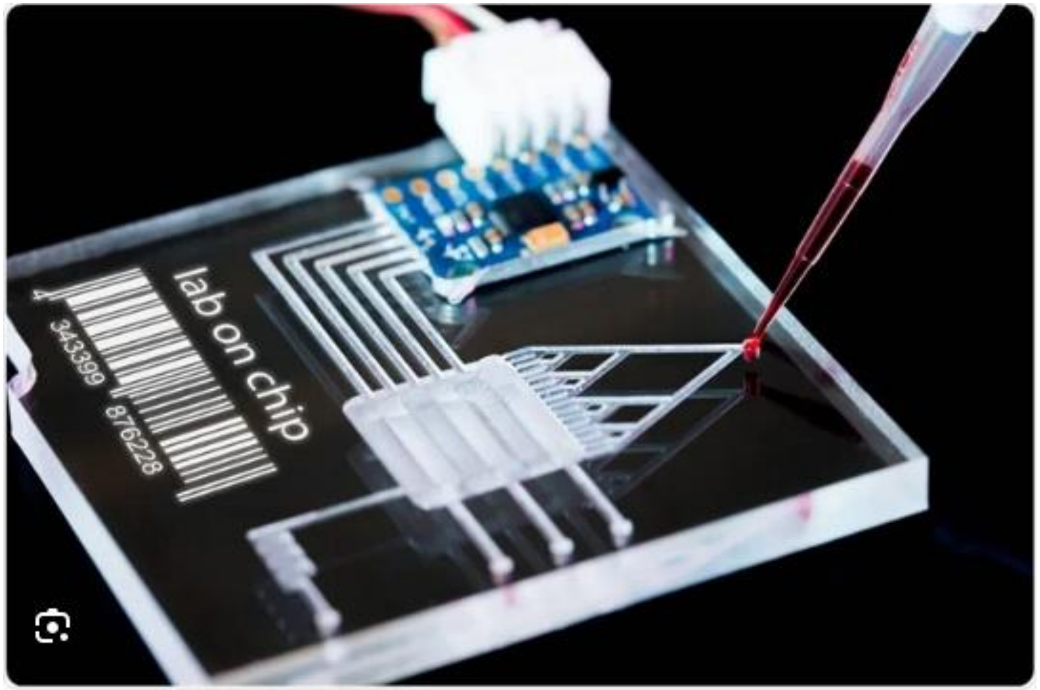
Introduction

Surface acoustic waves (SAW) for particle manipulation

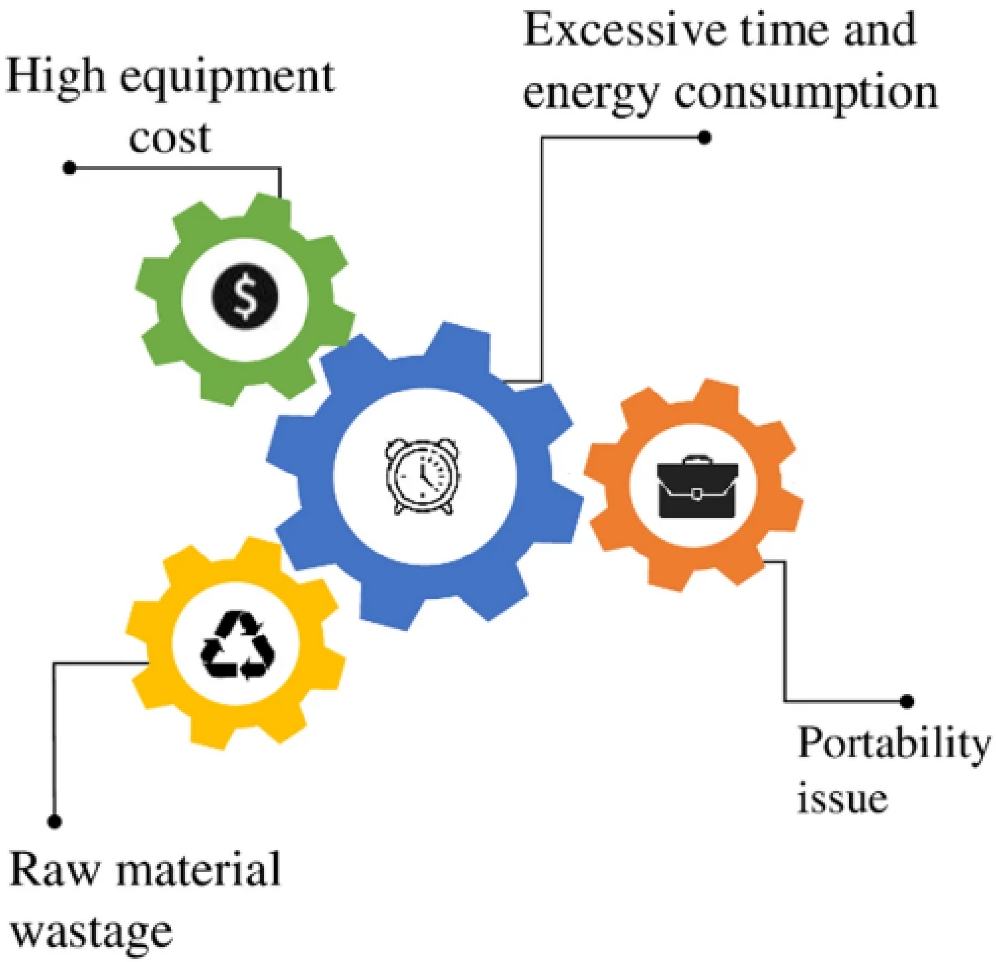
- Introduction to SAW-based tweezers
- Convex-Concave IDT electrodes for efficient separation of WBCs
- Surface coupled locally resonant modes
- Reinforced and localized SAW-based tweezers
- SAW-in-capillary separation of highly motile sperm
- Acoustic treatment in freezing/thawing of sperm
- SAW-biosensor for detection of Cardiac Troponin I

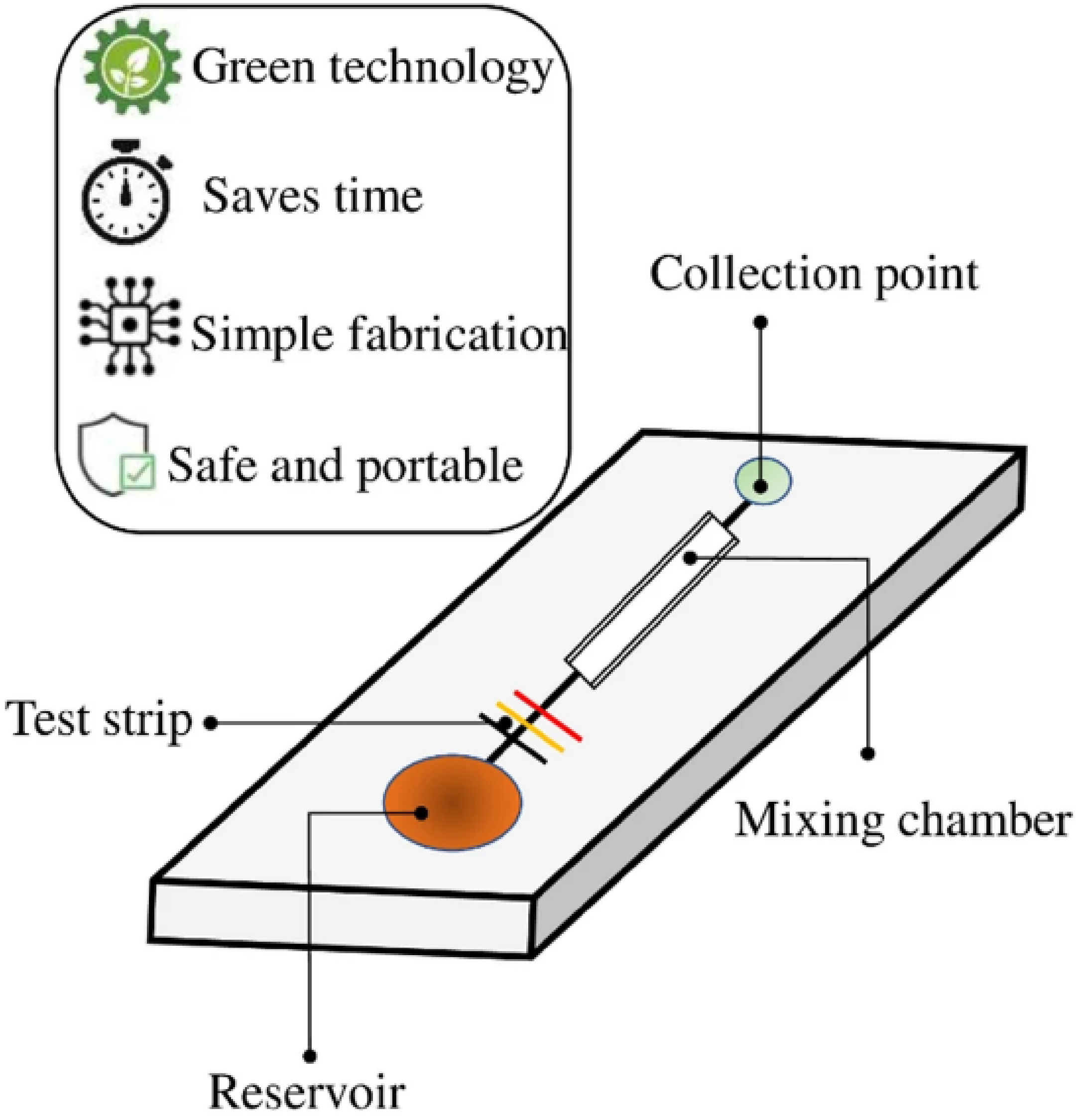
Microfluidics and Lab-on-chip

- Microfluidic systems are non-turbulent, highly ordered, fluid flow systems that are typically used in controlled biological experiments.
- The size of microfluidic devices is about a few hundred microns.
- The ability to put an entire laboratory procedure into a simple microsystem has given this technology the name “lab on a chip”
- Within the microfluidic chip, fluids are mixed, separated or directed, as the experiment requires.
- The outcome is an automated multiplexed system which can achieve high throughput.



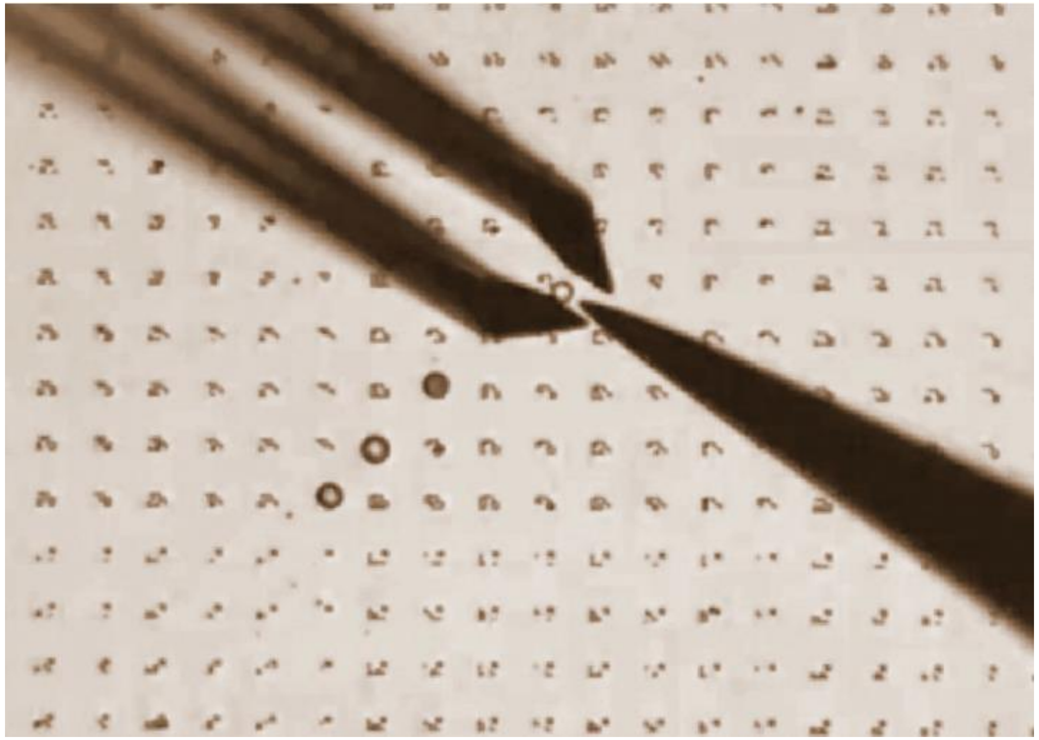
Clinical analysis versus Lab-on-chip



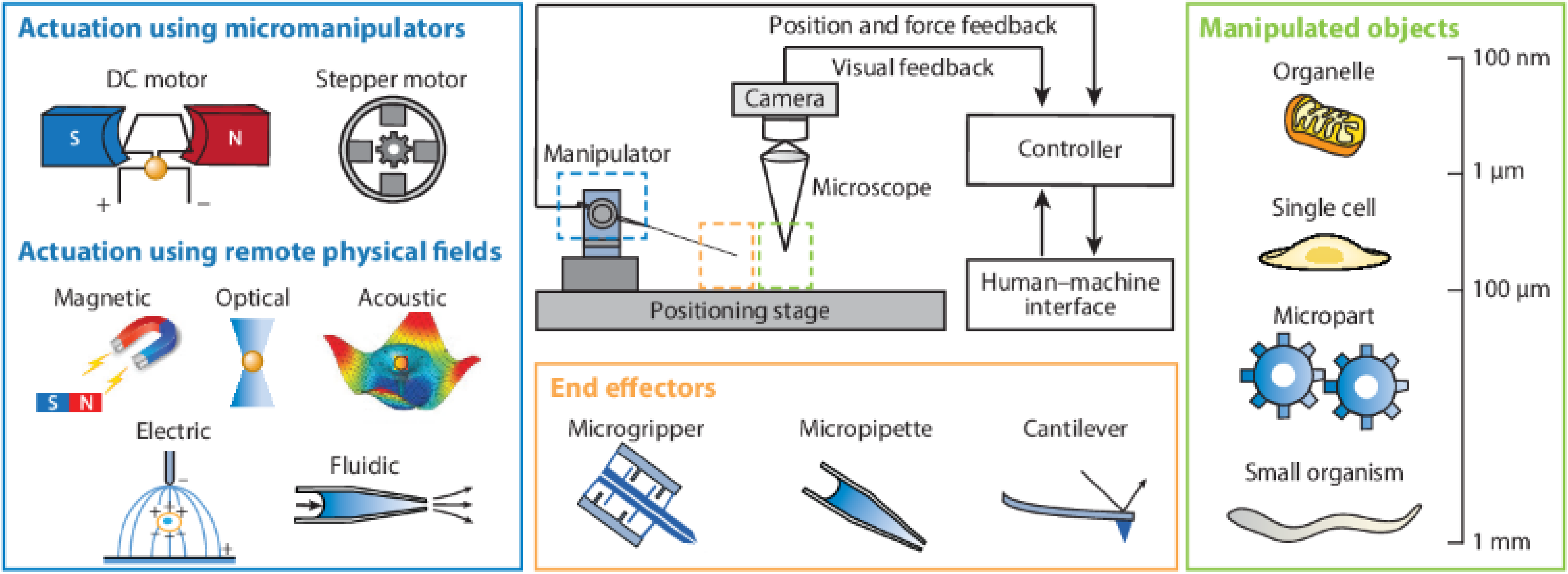


Manipulation of target particles

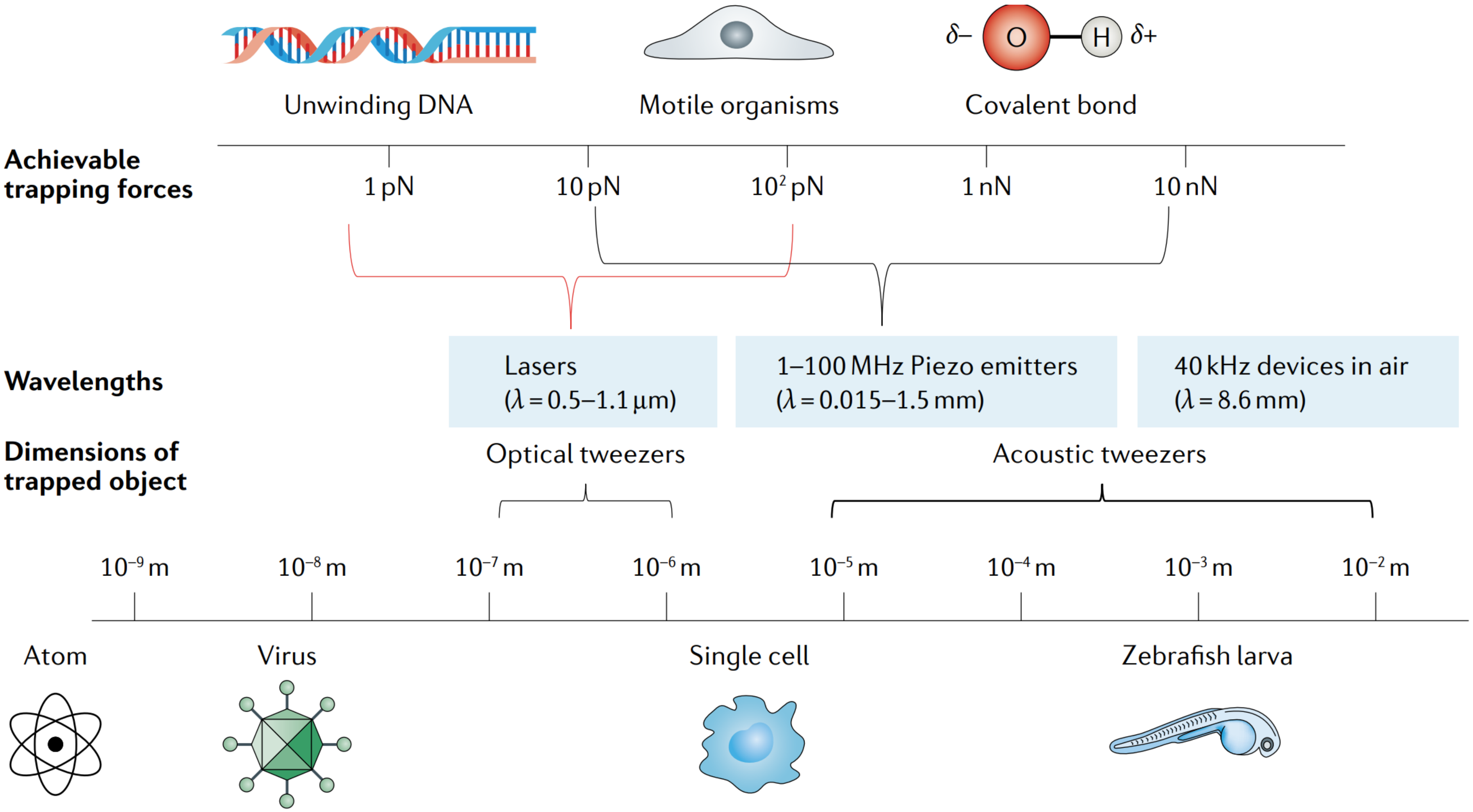
Reducing the particle size



Manipulation of target micro-particles



Acoustic/optical manipulation of micro-particles

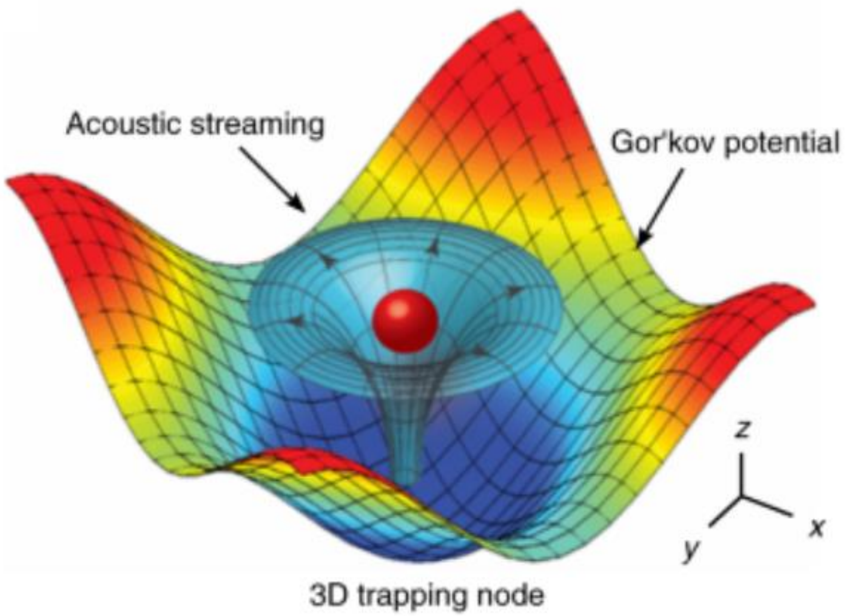


Nature Reviews Physics volume 2, pages480–491 (2020)

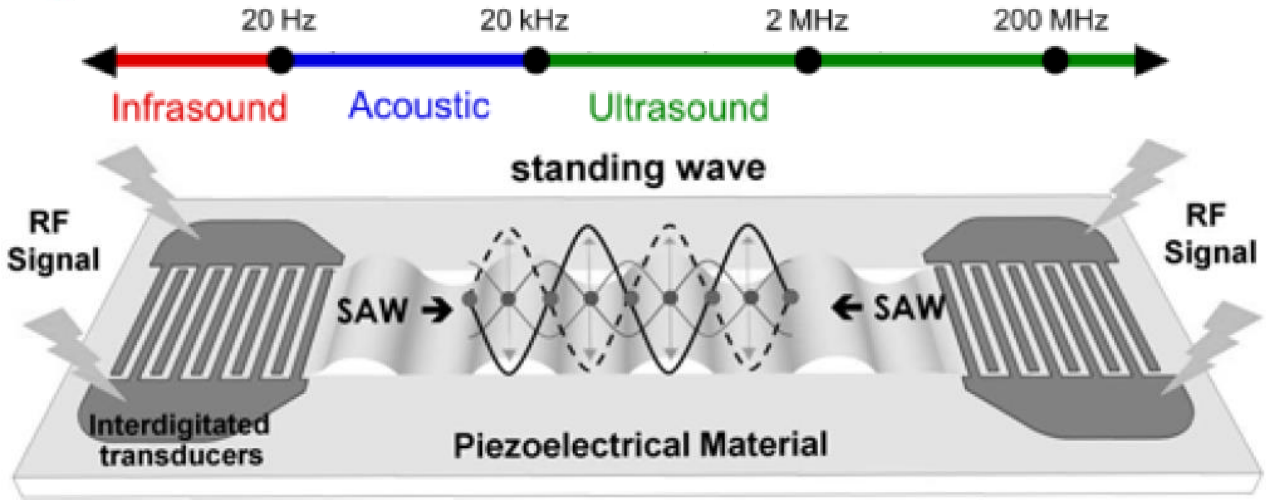
Advantages of Acoustic Tweezers

Advantages of Acoustic Tweezers

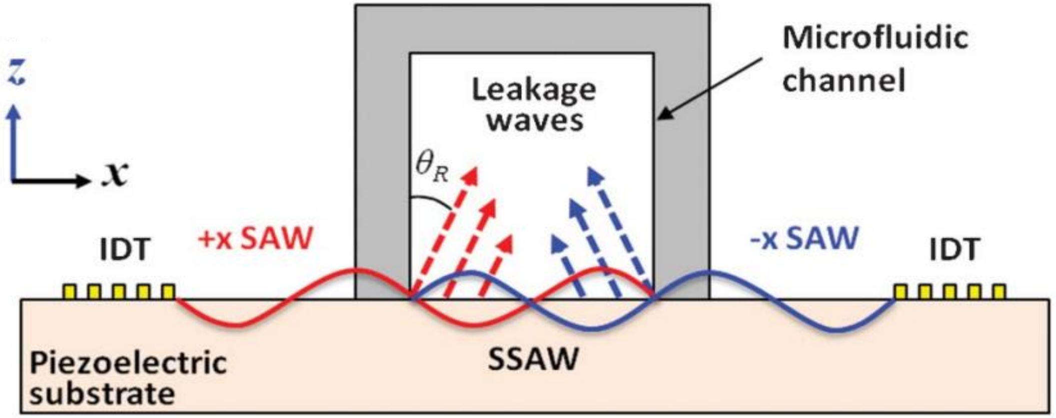
- Non-invasive
- Biocompatible
- Label-free
- Non-contact
- Contamination-free



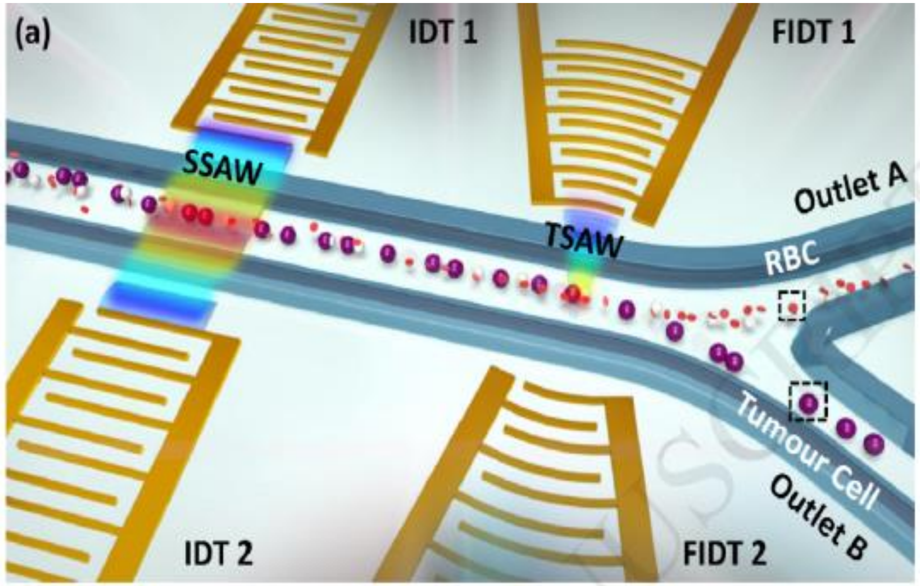
SAW-based manipulation of micro-particles

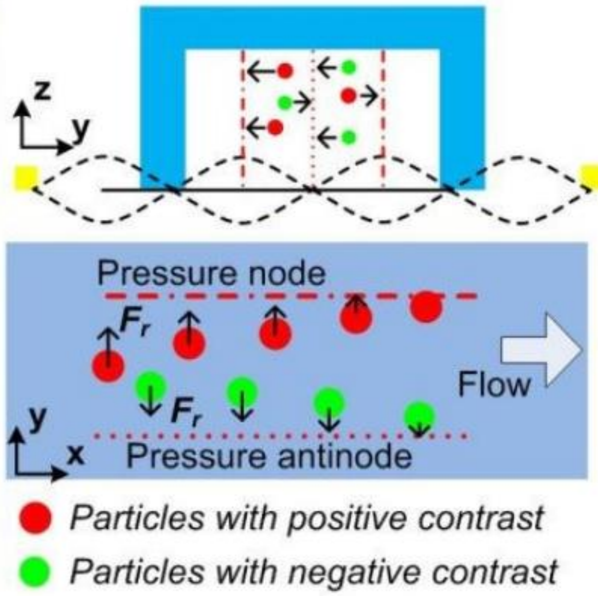


J. Nam, et al., (2011),Korea- Aust Rheol. J.



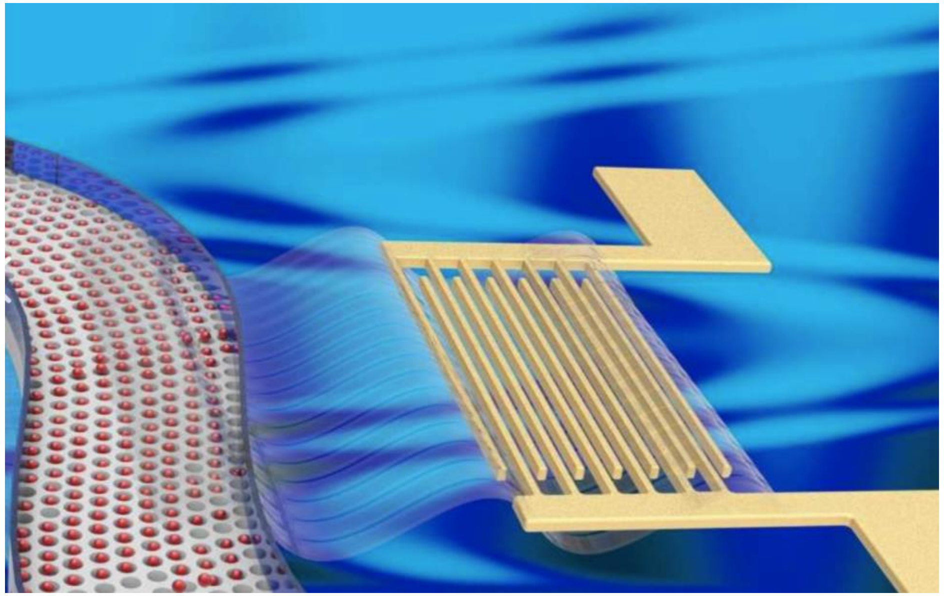
X. Ding, ***Lab Chip***, 2013

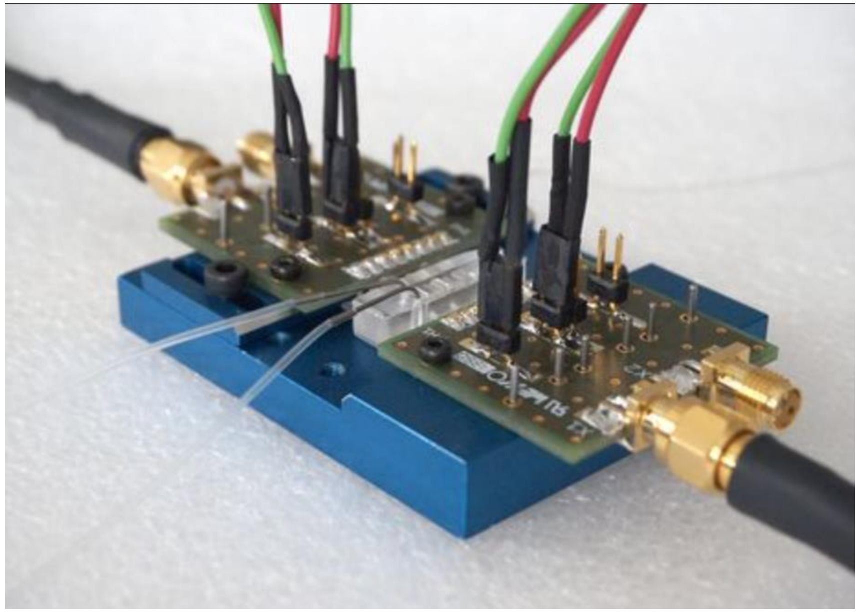


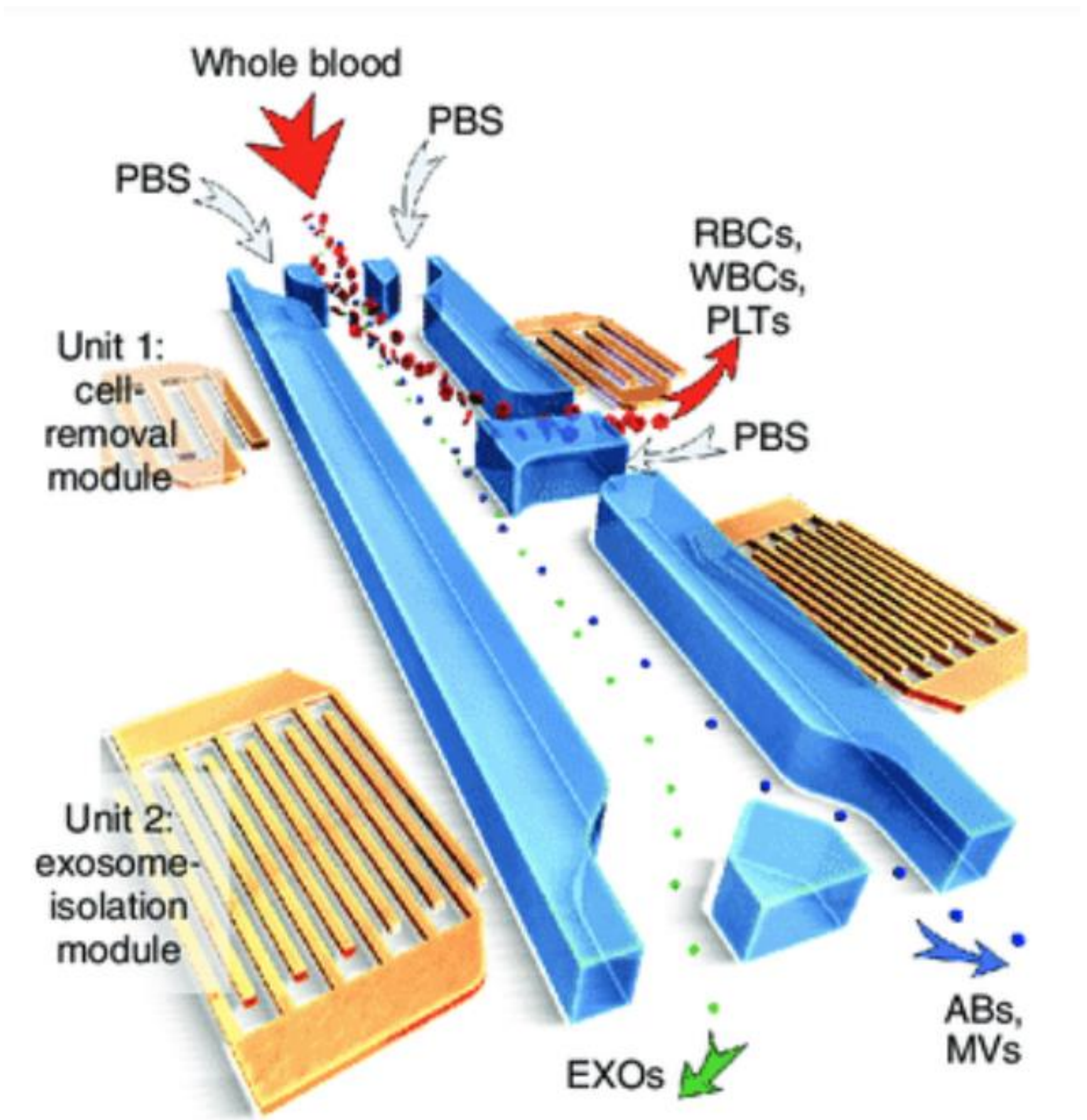


M. Wu et al., ***Lab Chip***, 2019

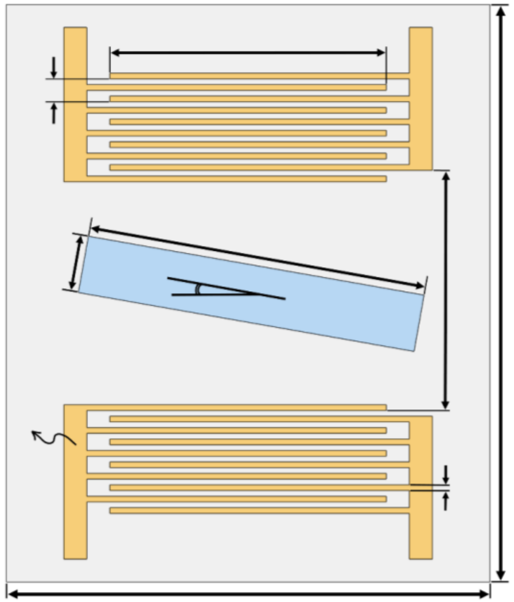
Acoustofluidic: Acoustic Manipulation in Microfluidics

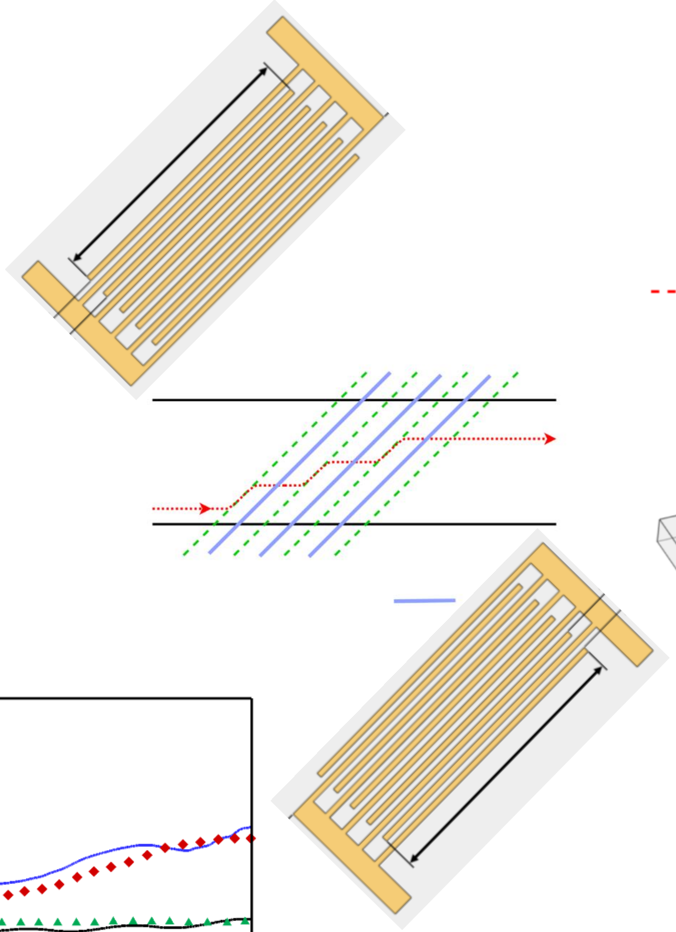


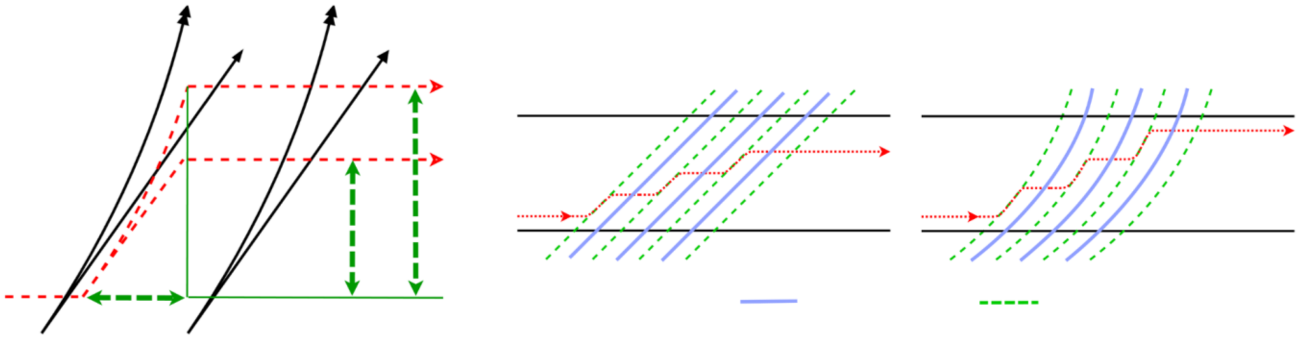


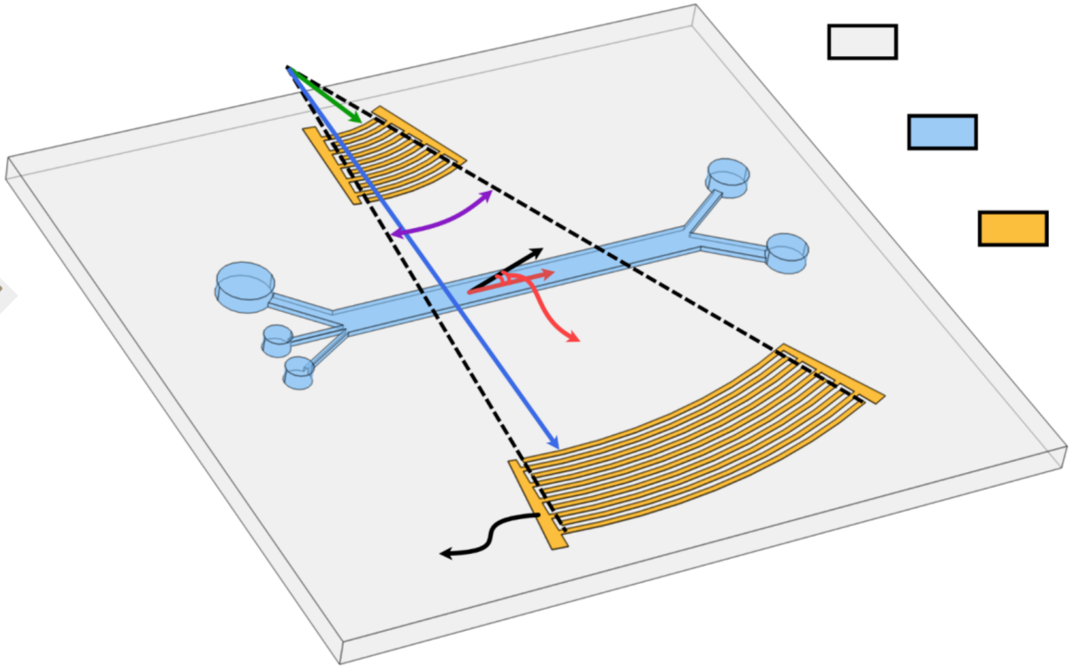


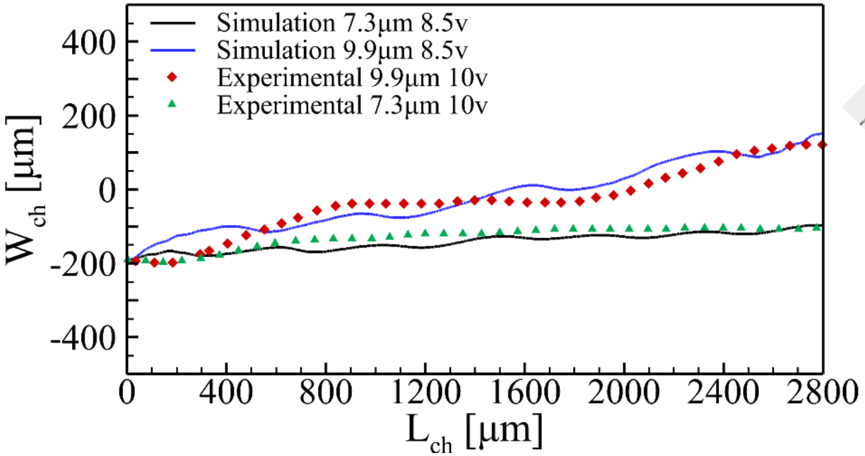
SAW-based separation of WBCs by concave/convex IDTs





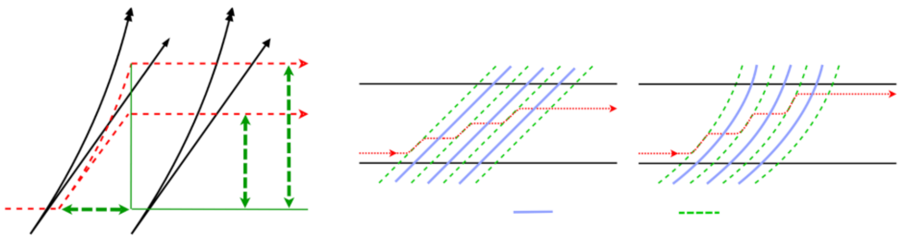


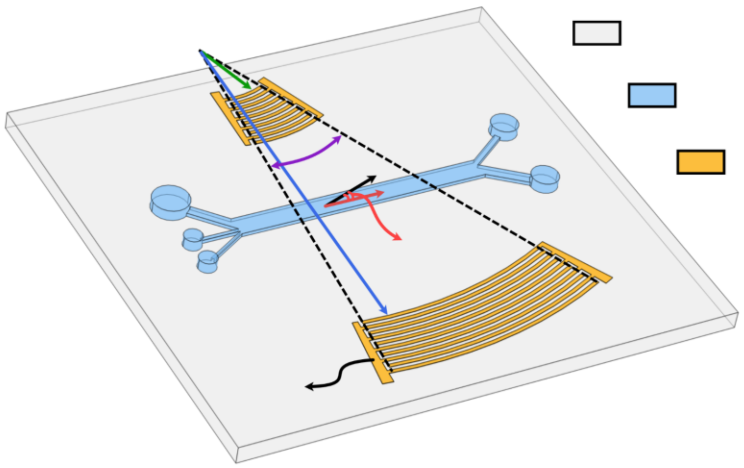


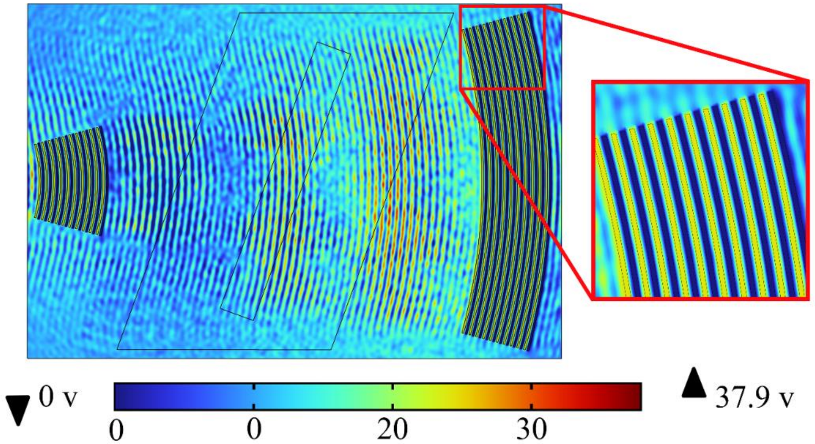


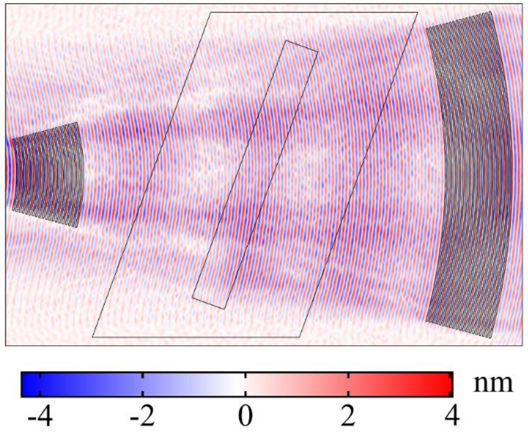
SAW-based separation of WBCs by concave/convex IDTs

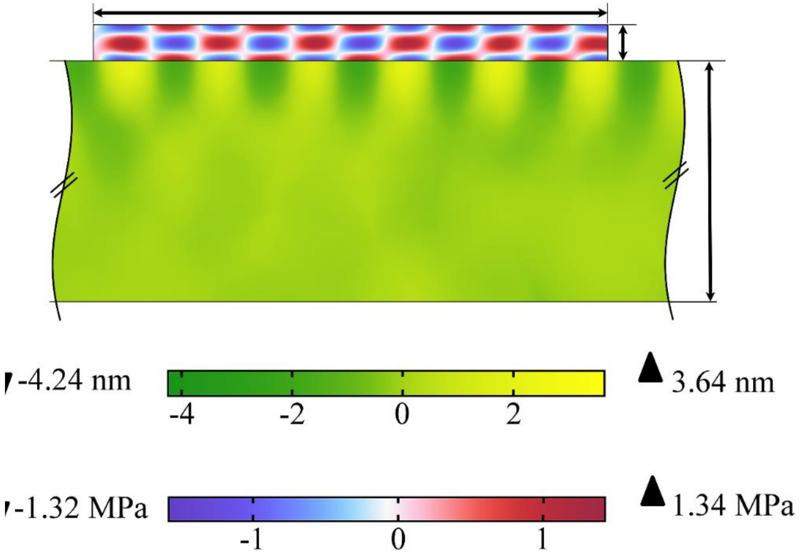
Separating lymphocytes from other WBCs, as a demonstration of separating close-sized bio-particles.

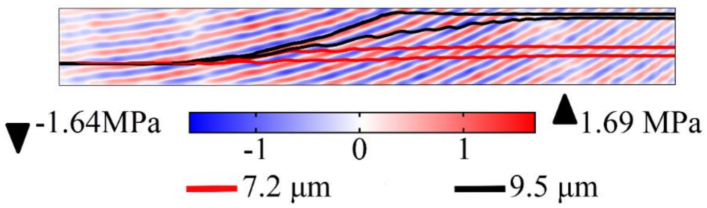


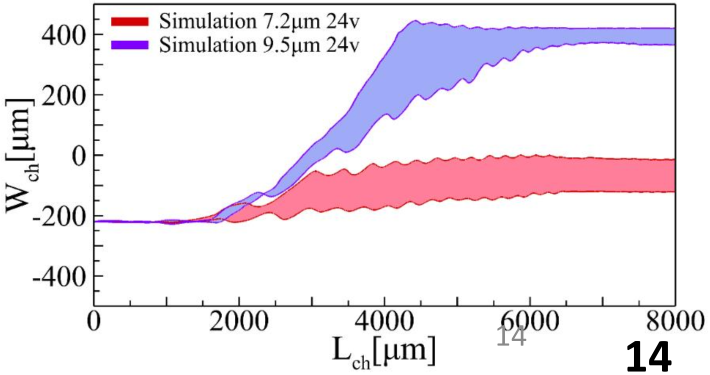










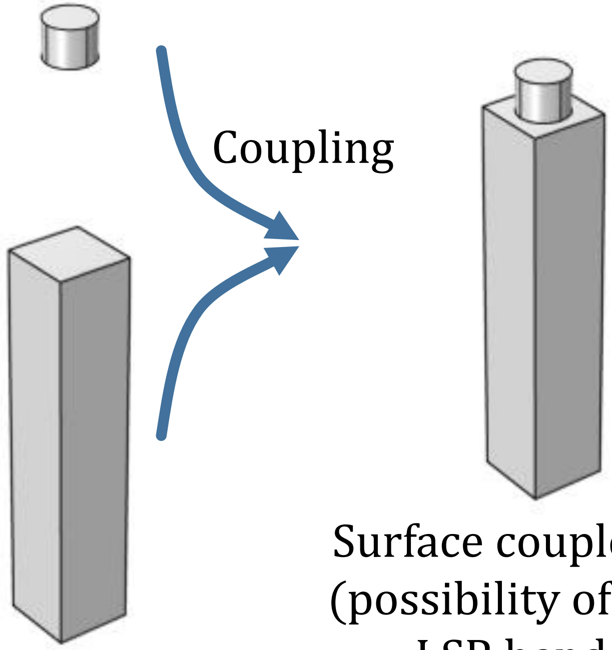


Locally Resonant Surface Coupled Modes (LRSCM)

Physics of LRSCM

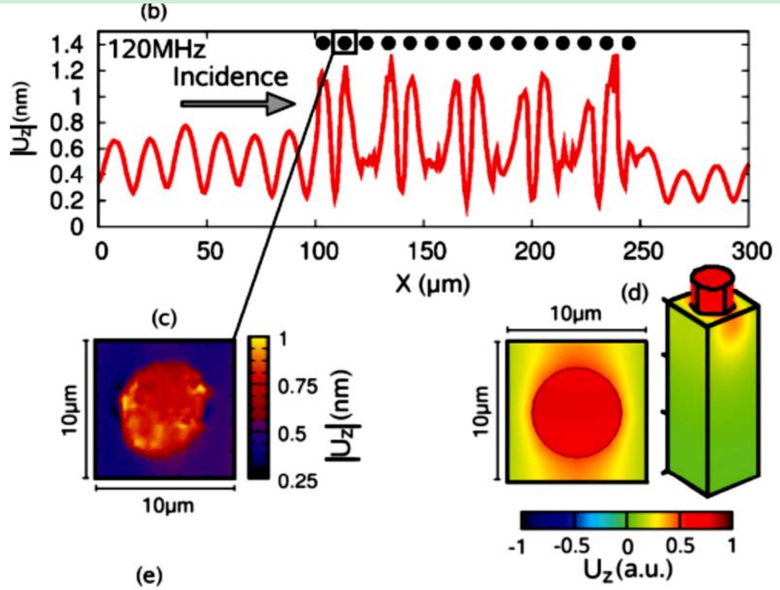
Resonance modes (pillar)

Surface modes (substrate)

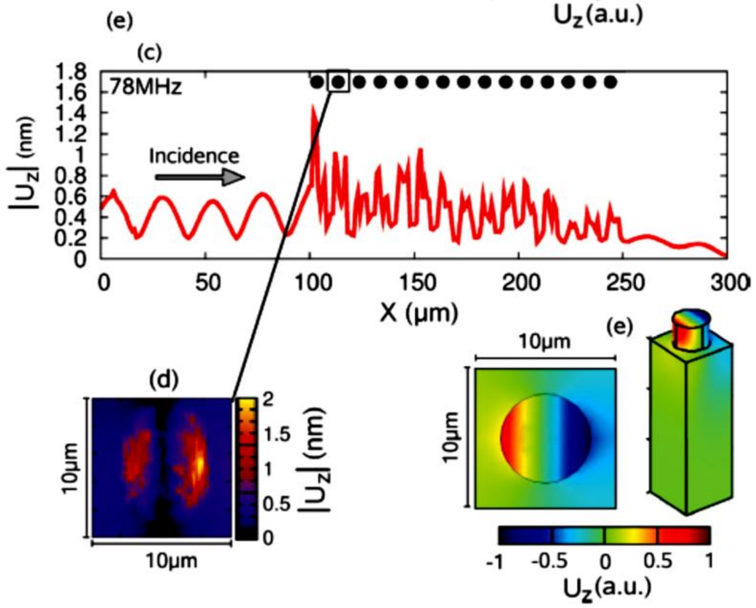


Surface coupled mode (possibility of opening LSR bandgap)

LRSC



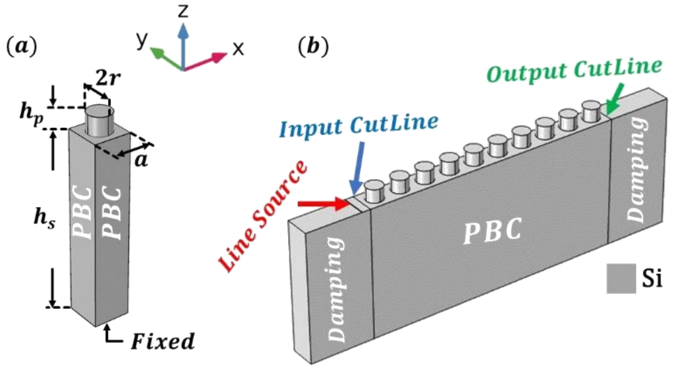
Bragg



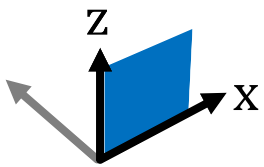
Achaoui Y., et al., *Phys. Rev. B*, 2014

Locally Resonant Surface Coupled Modes (LRSCM)

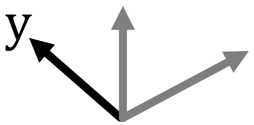
Pillar-Based PnC

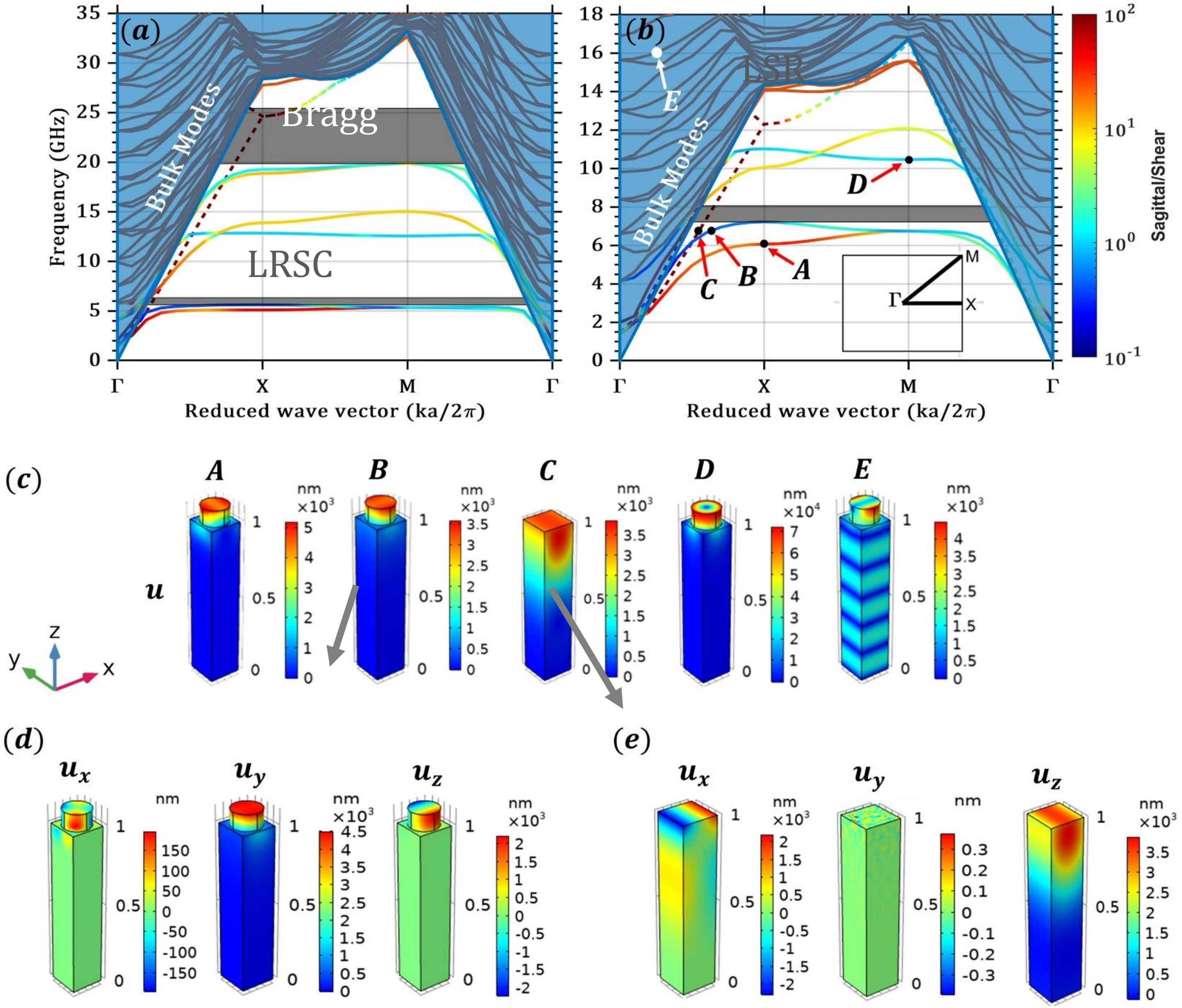


Sagittal polarization:



Shear polarization:

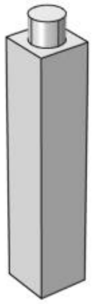


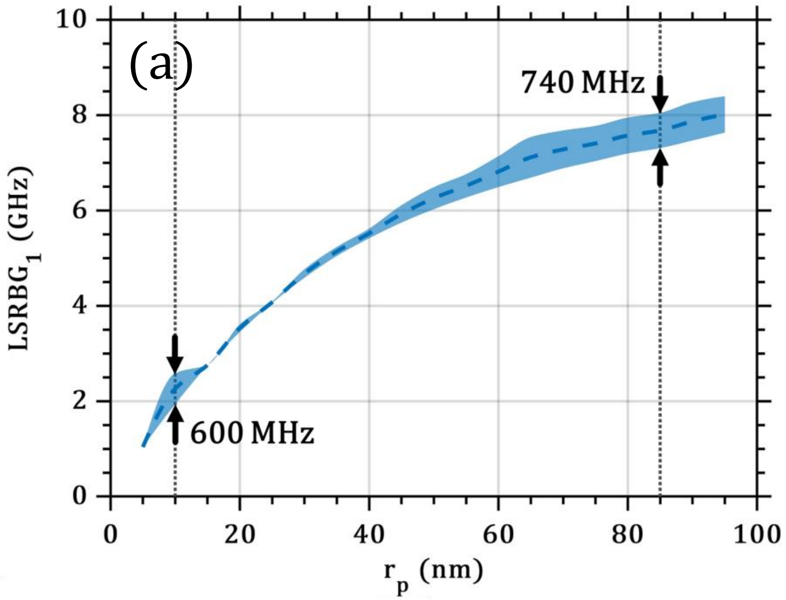


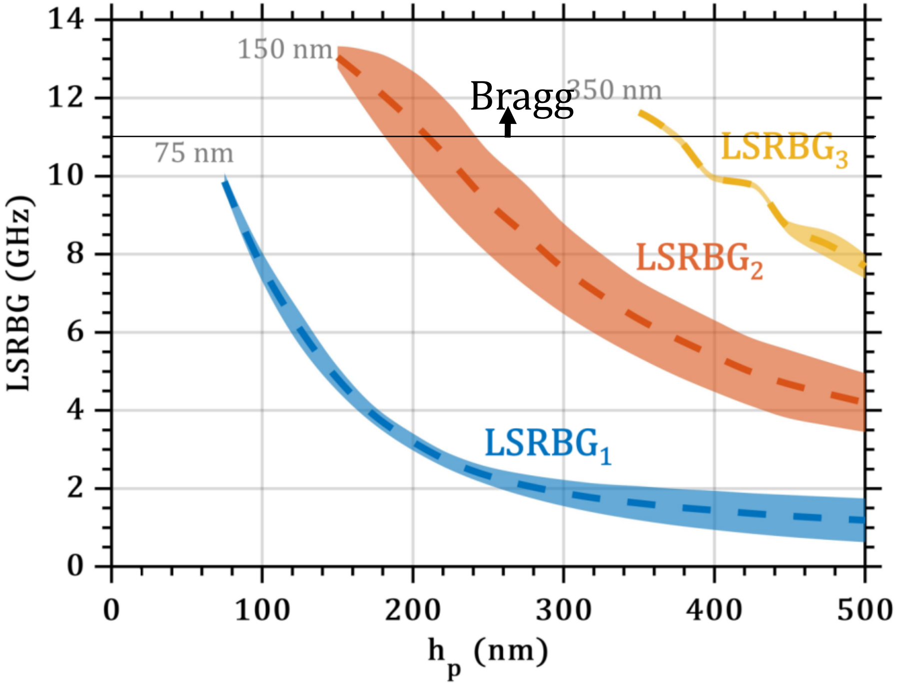
Locally Resonant Surface Coupled Modes (LRSCM)

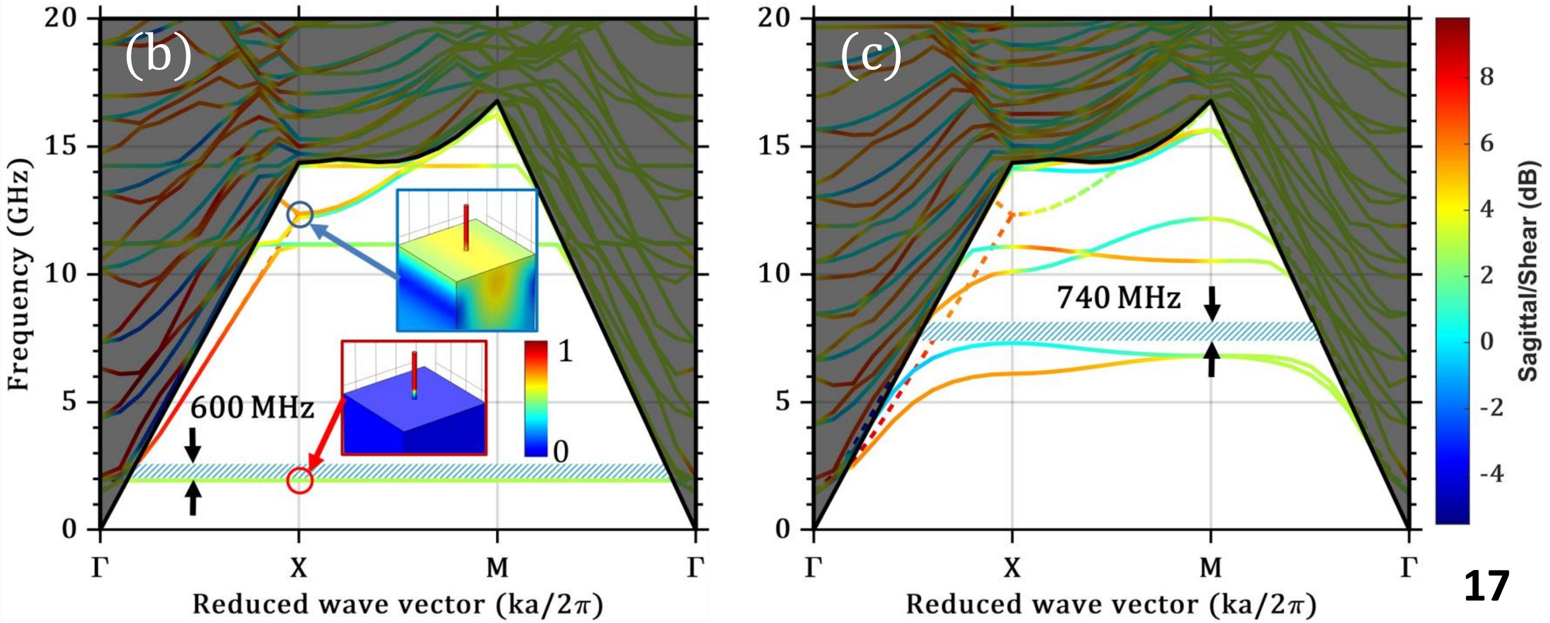
Pillar-Based PnC

LRSC Bandgap Central Frequency

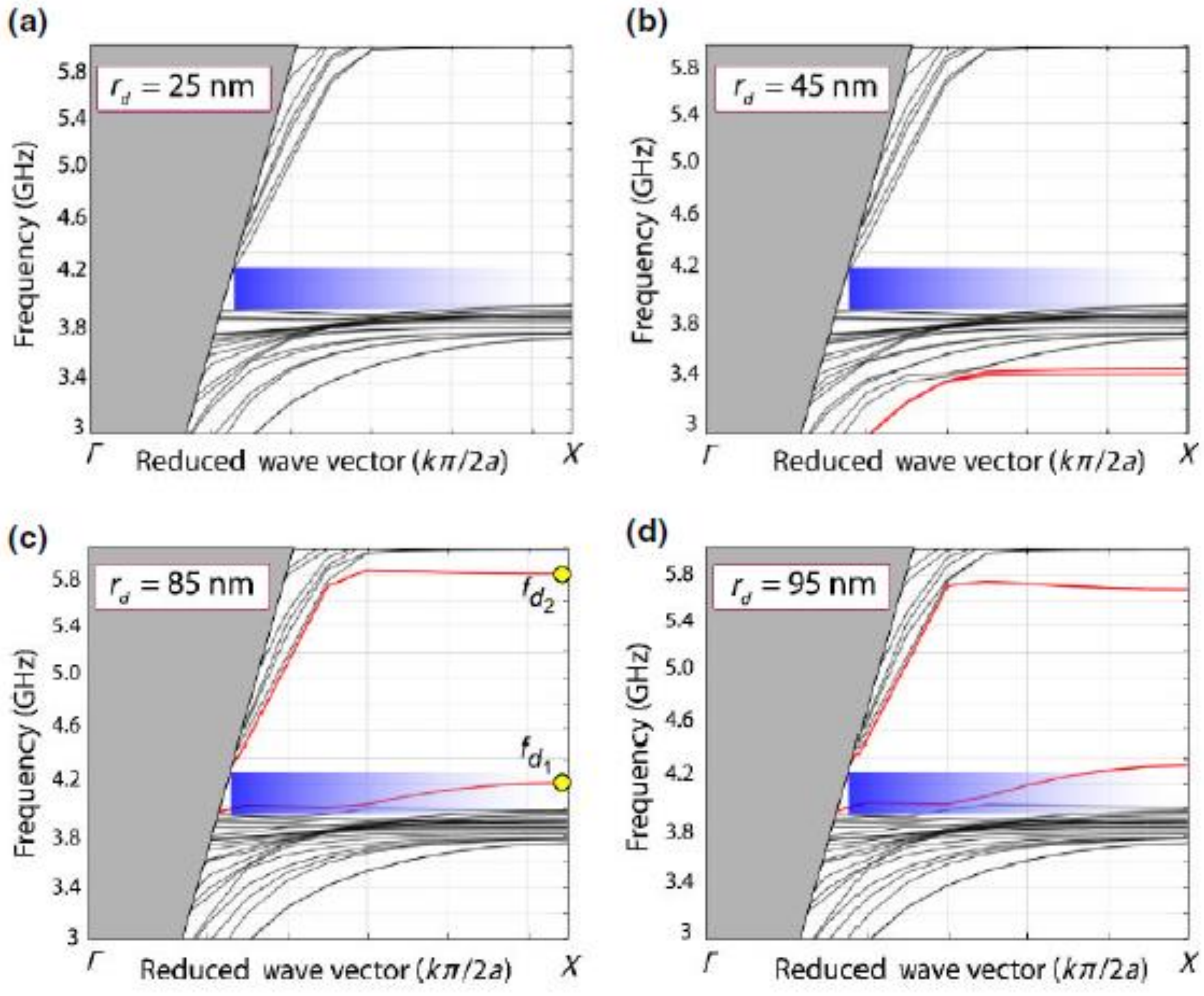


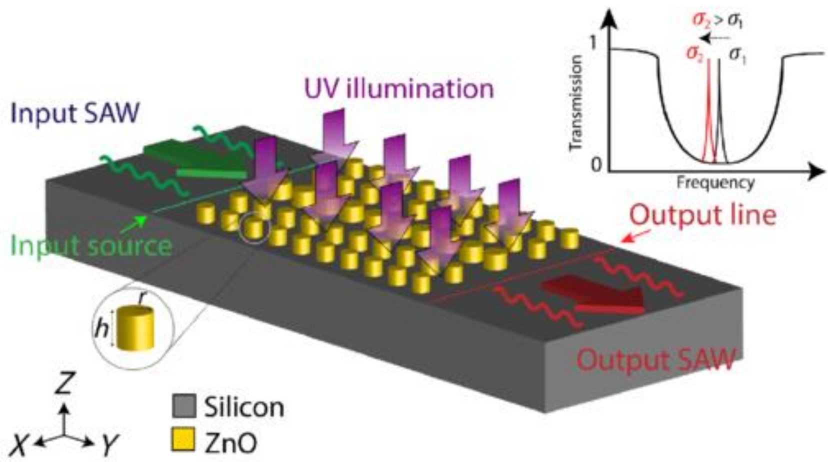


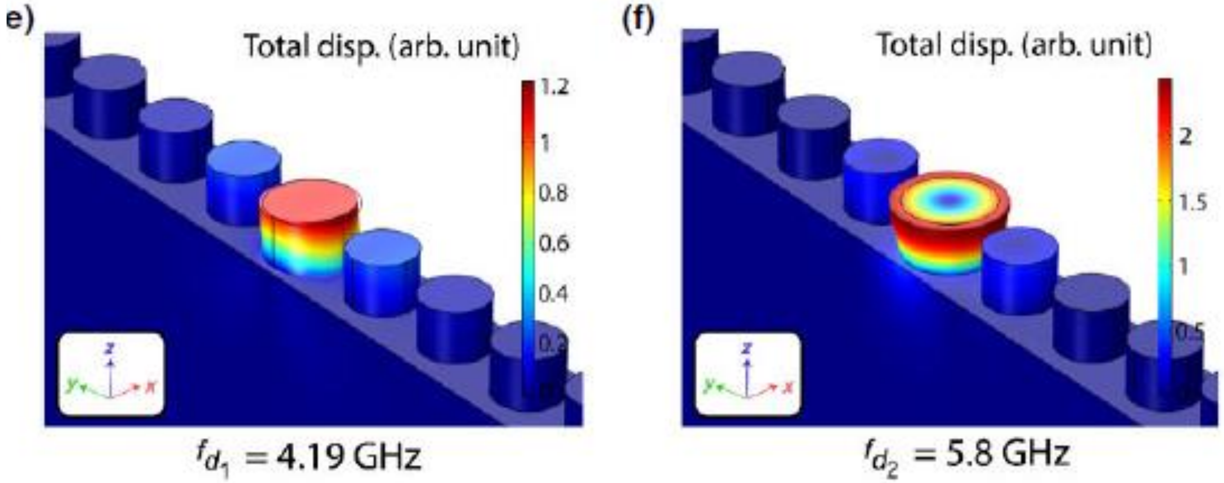




Localized LRSC Modes in defects

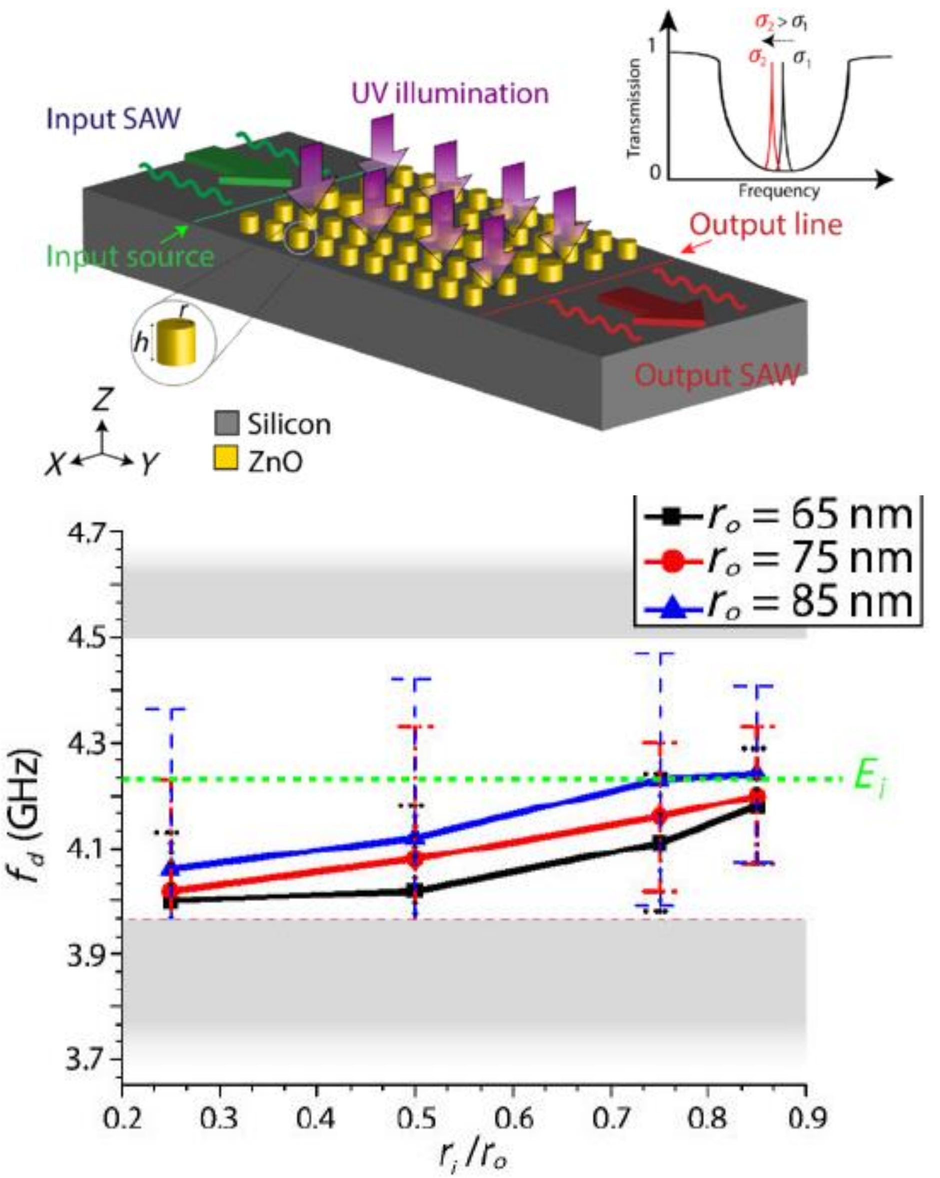


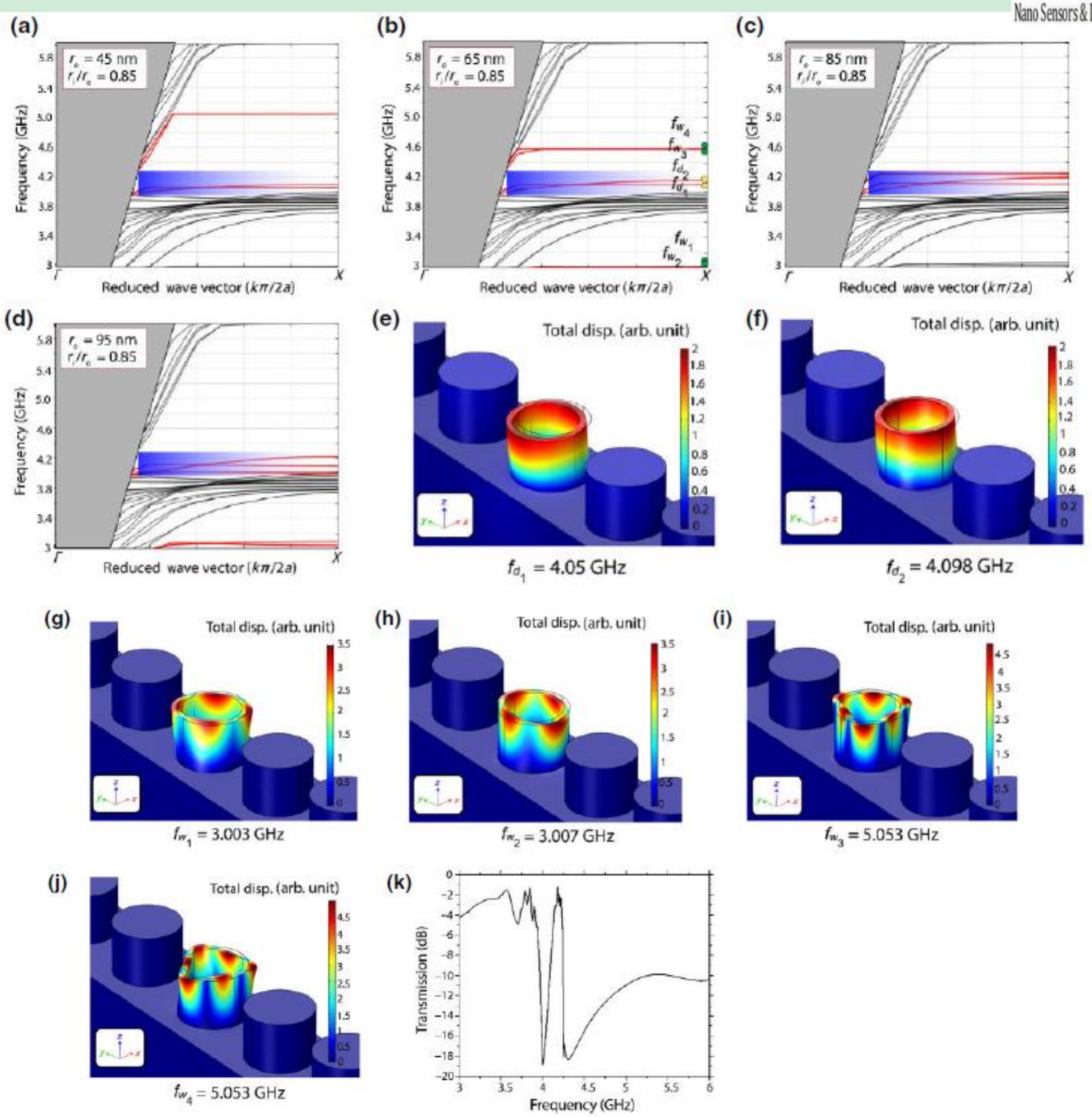




Taleb, *et al. Physical Review Applied* 2019.

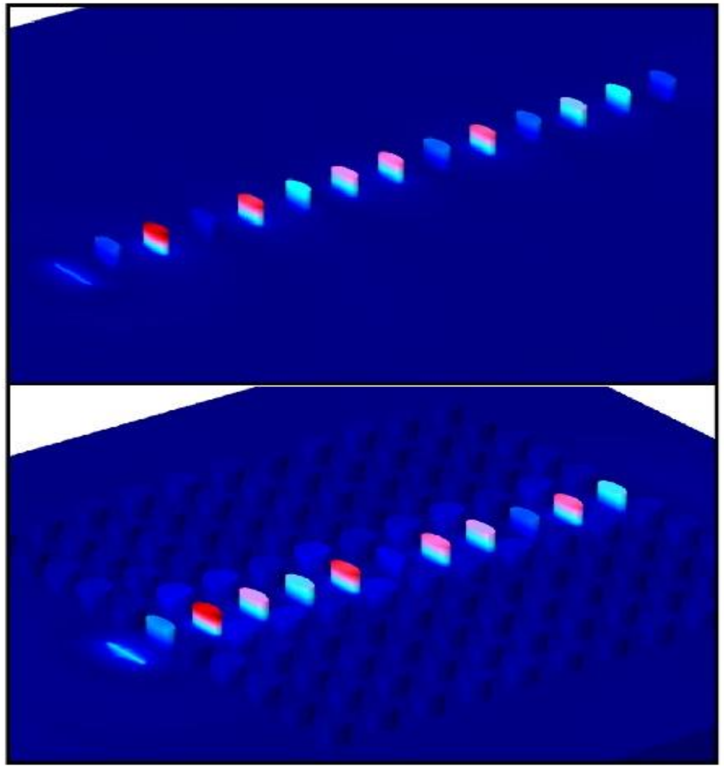
Localized LRSC Modes in defects



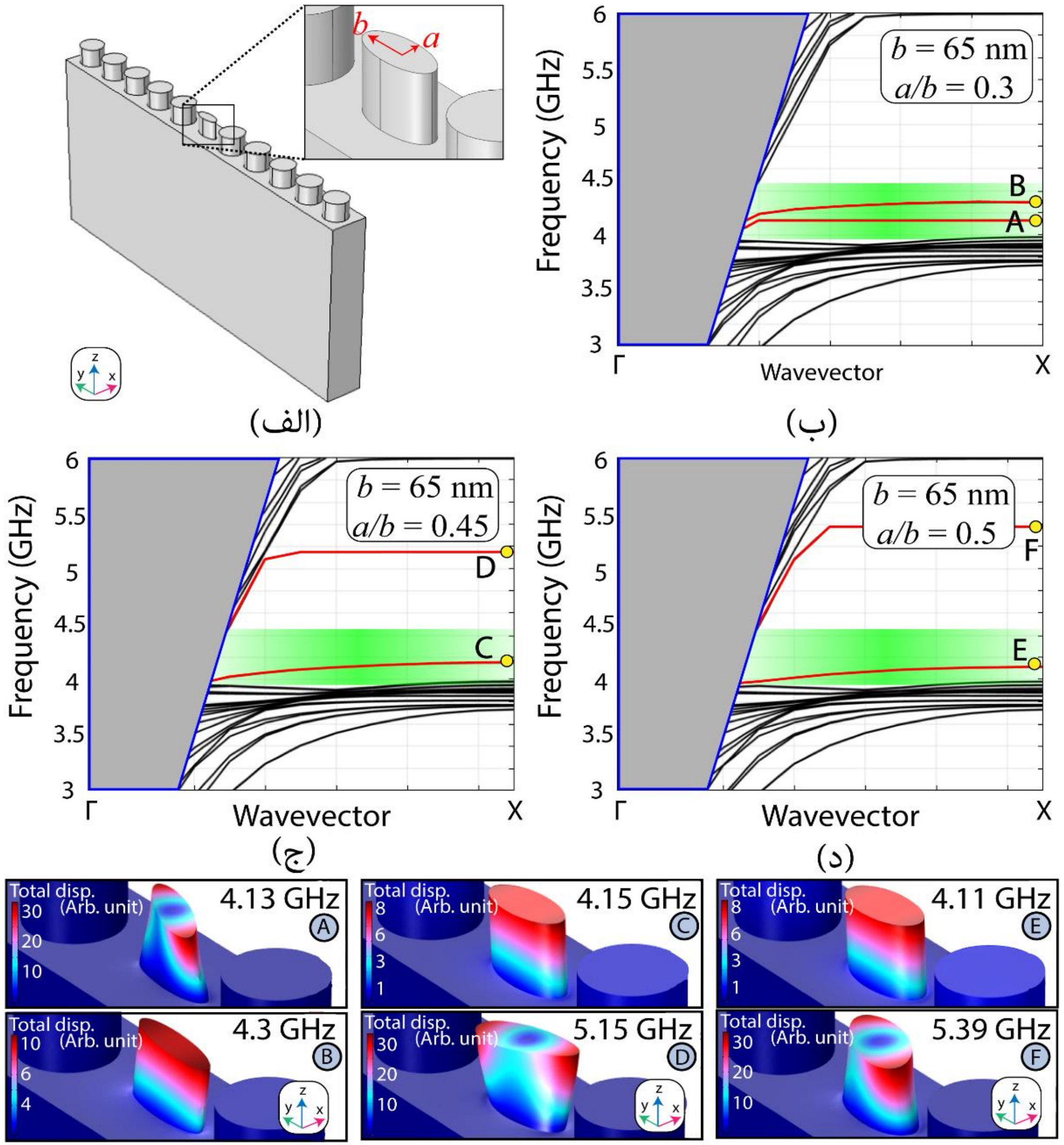


Taleb, *et al. Physical Review Applied* 2019.

Localized LRSC Modes in defects

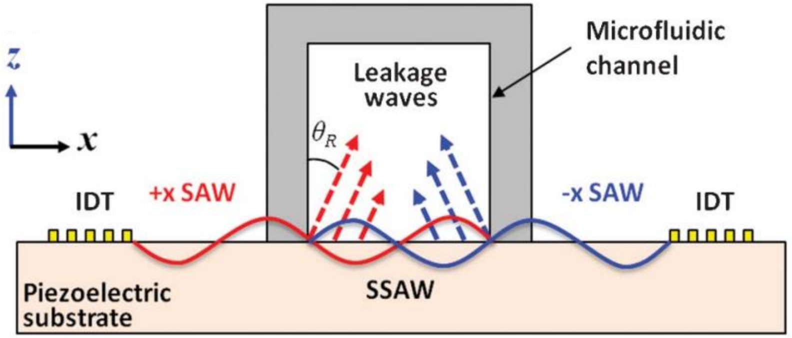


f_d=4.2 GHz



Taleb, *et al. Journal of Physics D: Appl. Phys.* 2021.

Basic Principles of Acoustofluidics



X. Ding, ***Lab Chip***, 2013

Governing equations in the fluid:

- $p = p(\rho)$
- Continuity equation : $\partial_t \rho = -\nabla . (\rho v)$
- Navier-stokes equation : $\rho \partial_t v = -\nabla p - \rho(v.\nabla)v + \eta \nabla^2 v + \beta\eta\nabla(\nabla . v)$

Fluid pressure, velocity and density, up to second order of perturbation:

- $p = p_0 + p_1 + p_2 + \ldots$
- $v = v_0 + v_1 + v_2 + \ldots$
- $\rho = \rho_0 + \rho_1 + \rho_2 + \ldots$

H. Bruus, ***Lab Chip***, 2012

First- and Second-Order of Acoustic Fields

First-order fields:

$p_1 = \rho_1 {c_f}^2$

- $\nabla^2 p_1 = \frac{1}{{c_f}^2} {\partial_t}^2 p_1 \quad , \eta = 0$
- $\rho_0 \partial_t v_1 = -{c_f}^2 \nabla \rho_1 = \nabla p_1$
- $\partial_t \rho_1 = -\rho_0 (\nabla . v_1)$

Second-Order fields:

- $\rho_0 \nabla . < v_2 > = -\nabla . < \rho_1 v_1 >$
- $\nabla < p_2 > = -< \rho_1 \partial_t v_1 > - < \rho_0 (v_1 . \nabla) v_1 >$

H. Bruus, ***Lab Chip***, 2012

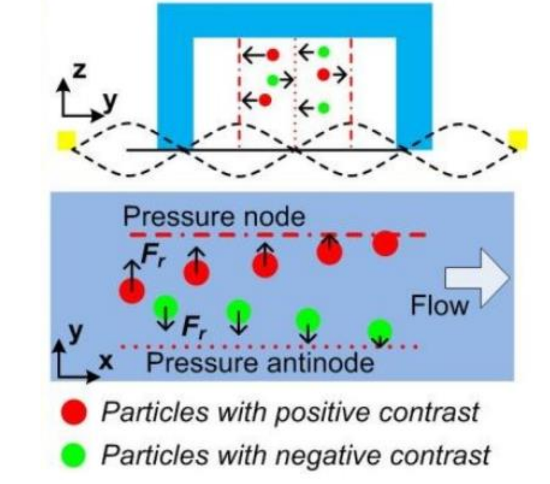
Acoustic Forces in Acoustofluidics

Motion of Particle:

$$m_p \frac{dv_p}{dt} = F_{rad} + F_{drag}$$

Nguyen et al., ***Appl. Phys. Lett.***, 2018

F_{rad}:



Acoustic Radiation Force:

$$F_{rad} = -\nabla U_{rad} = \frac{-4\pi}{3} R^3 \nabla\left[f_1 \frac{1}{2\rho_0 {c_f}^2} < p^2 > - f_2 \frac{3}{4} \rho_0 < v^2 >\right]$$

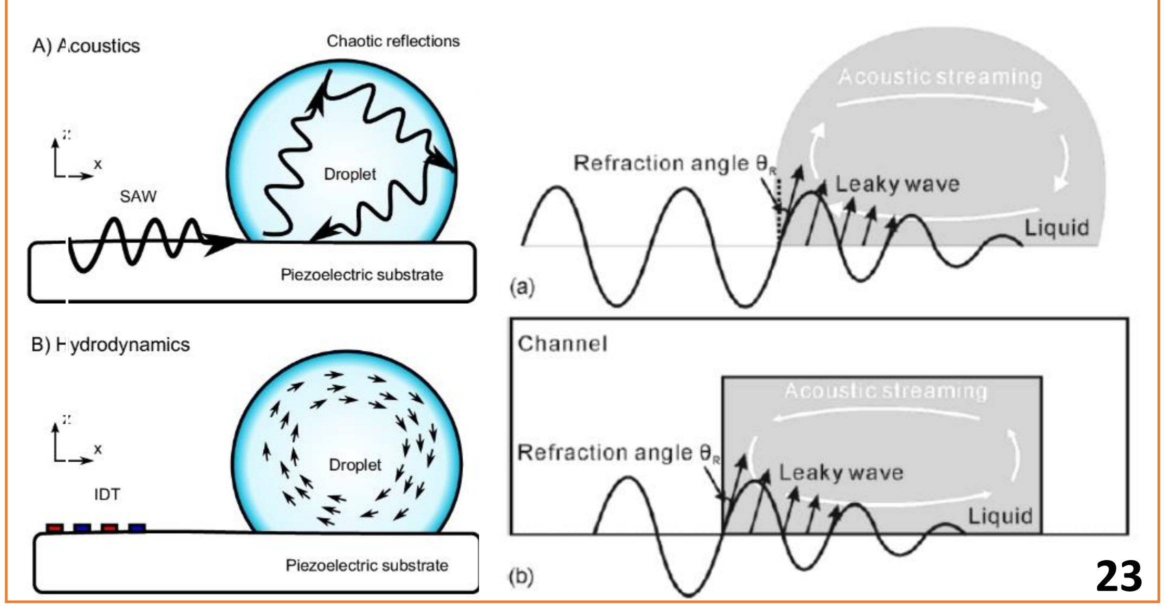
$$f_1 = 1 - \frac{k_p}{k_f}\ , \quad f_2 = \frac{2(\frac{\rho_p}{\rho_f} - 1)}{2(\frac{\rho_p}{\rho_f} + 1)}$$

Acoustic Induced Drag Force:

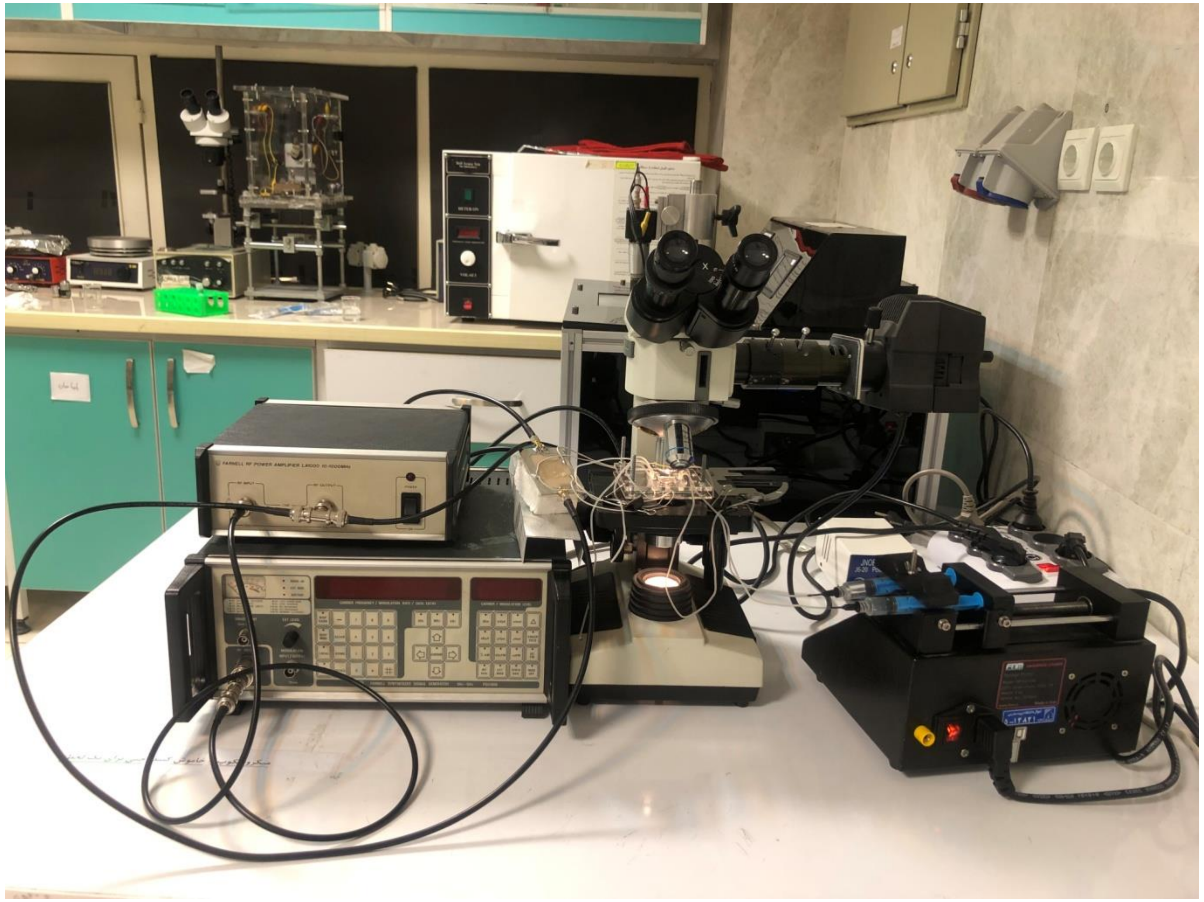
- $F_{drag} = 6\pi R\eta(< v_2 > - v_p)$

H. Bruus, ***Lab Chip***, 2012

F_{drag}:



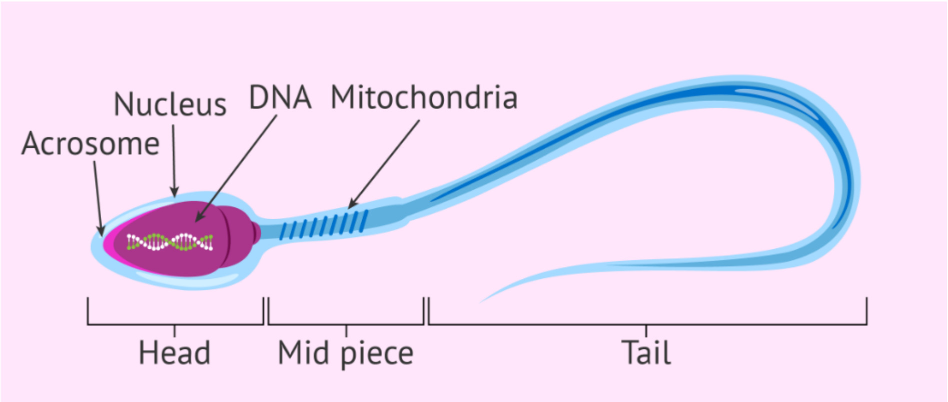
Acoustofluidics based on LRSCMs in SU-8 Ridges



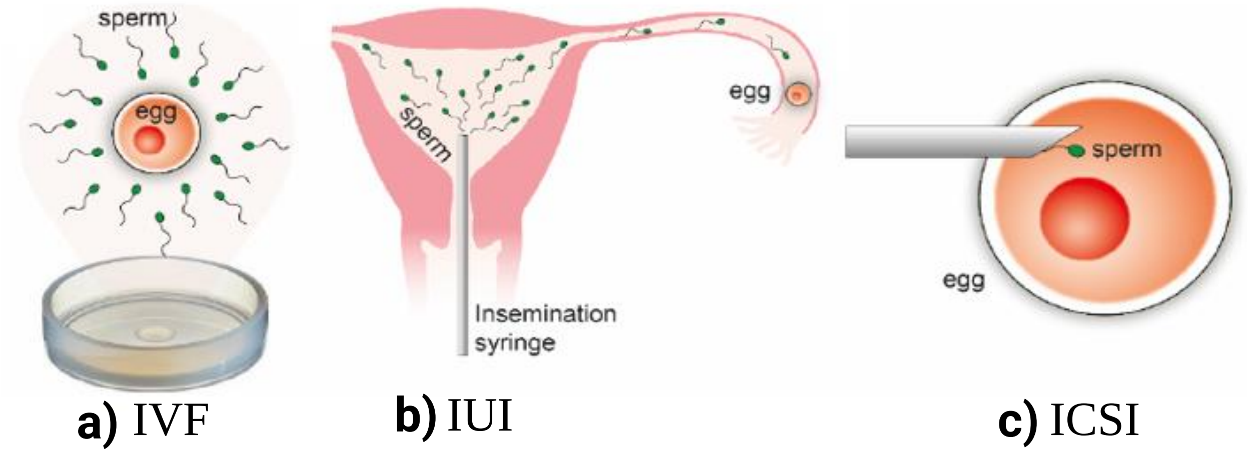
LiNbO$_3$-based Acoustofluidics

SAW-in-capillary for separating highly motile sperm cells

- ❖ The structure of human sperm consisting of a head and a flagellum
- ❖ Assisted reproductive technologies



Structure and parts of a sperm cell

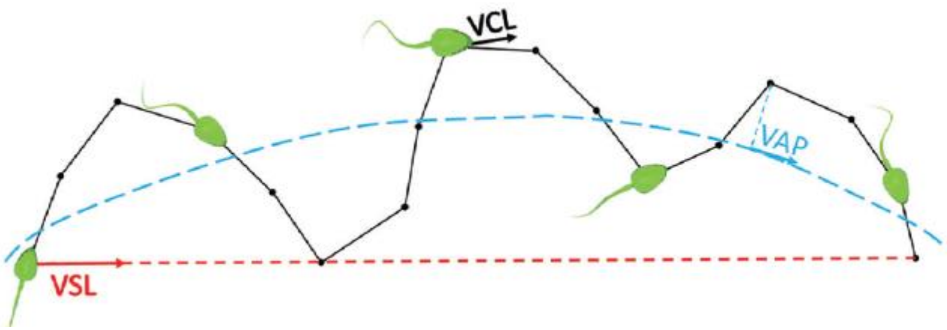


Assisted reproductive technologies a) In vitro fertilization b)Intrauterine Insemination c)Intracytoplasmic sperm injection

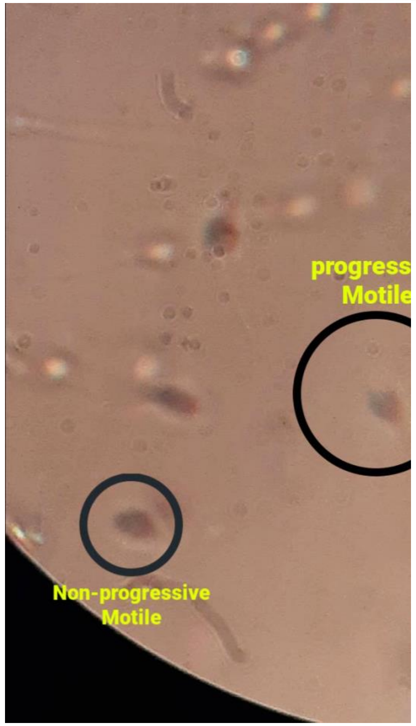
R. Nosrati, et al., Nature Reviews Urology, 2017.

SAW-in-capillary for separating highly motile sperm cells

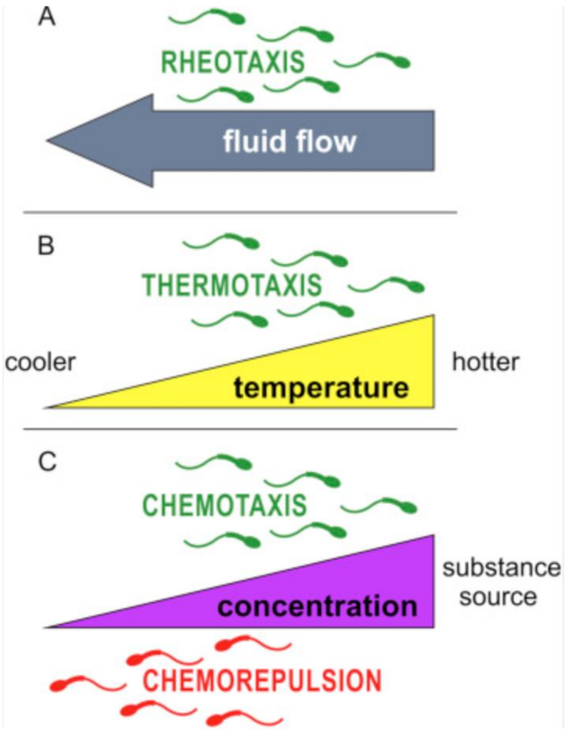
- ❖ Important parameters of sperm:
  - ❖ Motility
  - ❖ Vitality

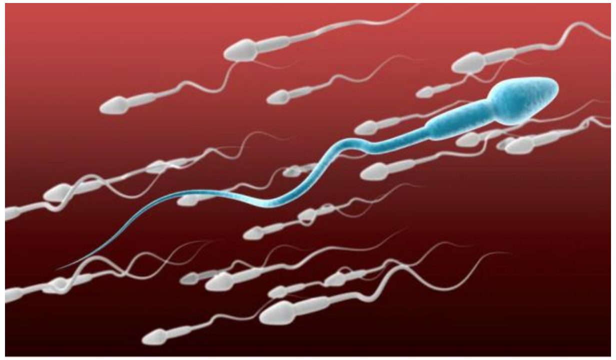


visual representation of kinematic velocities of sperm

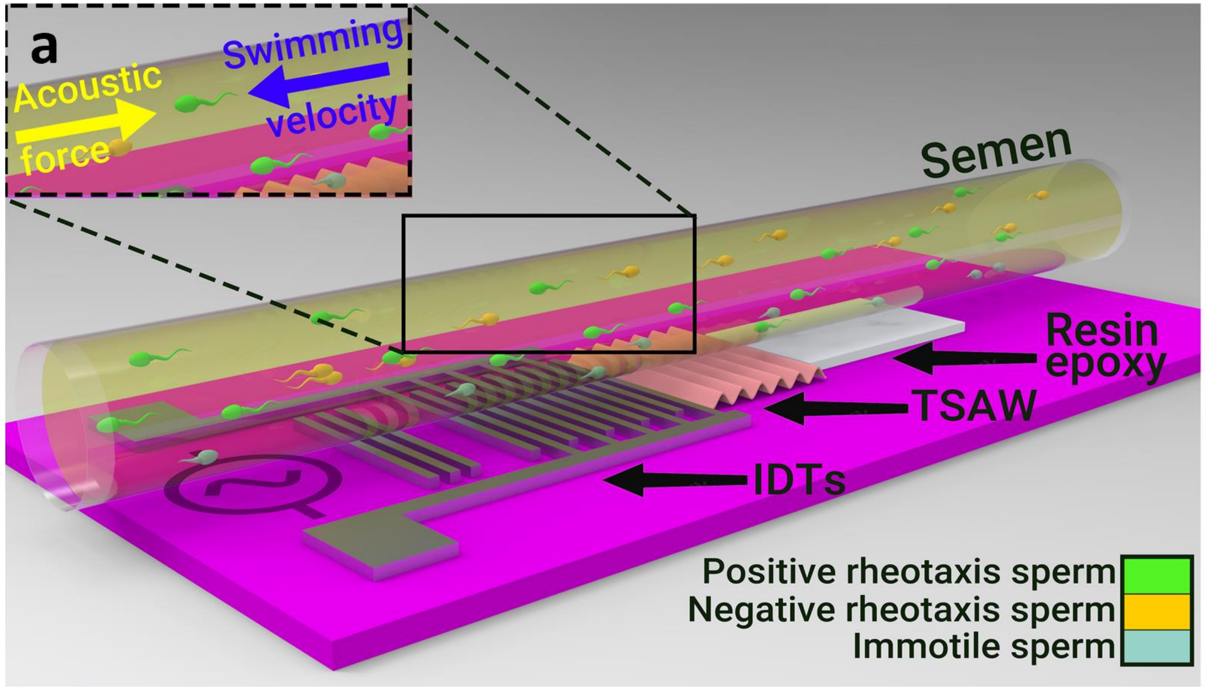


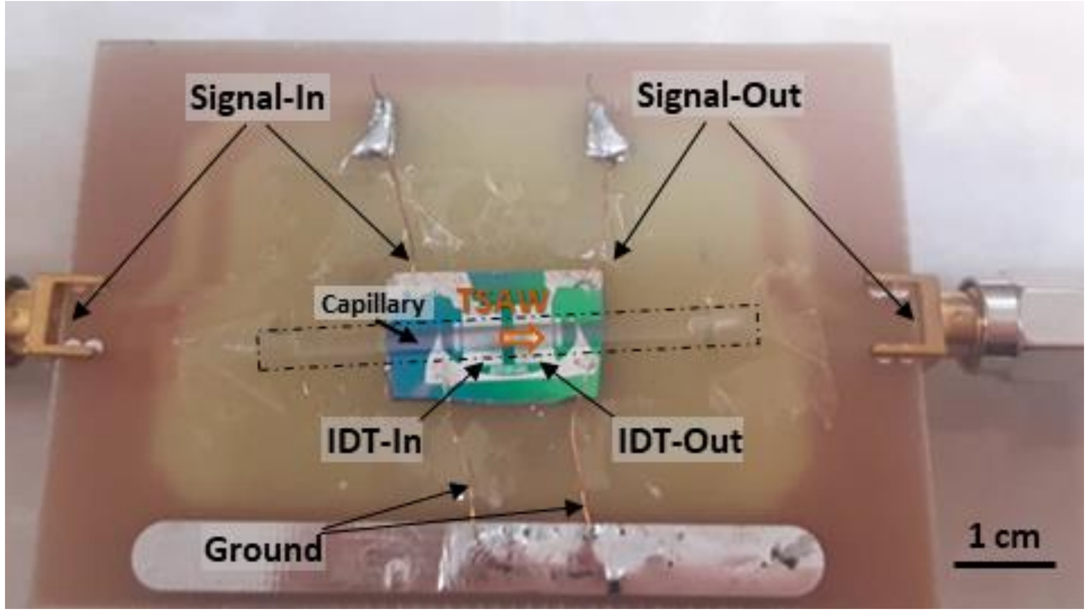
- ❖ Sperm natural behavior:
  - ❖ Rheotaxis
  - ❖ Thermotaxis
  - ❖ Chemotaxis
  - ❖ Acoustotaxis



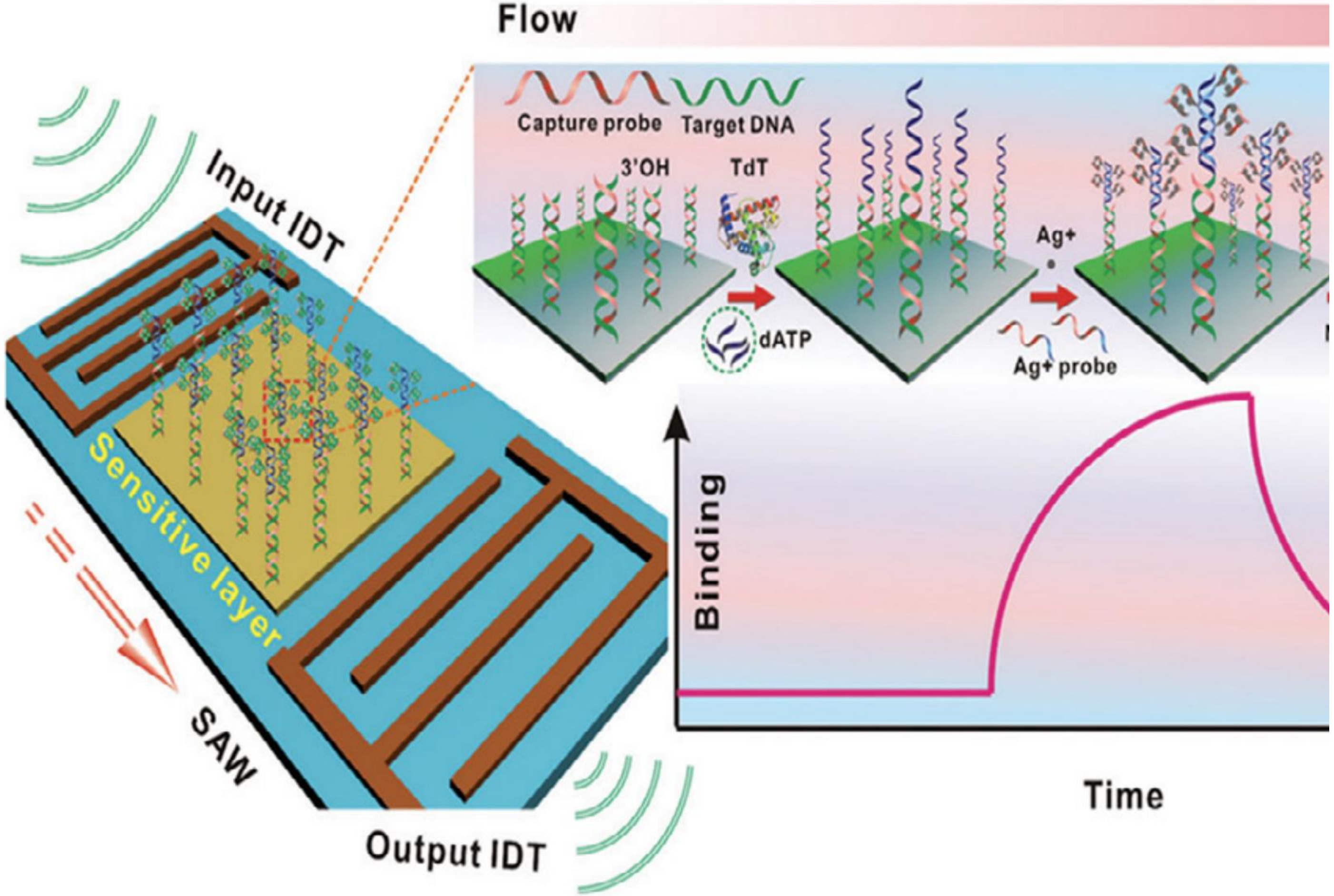


SAW-in-capillary for separating highly motile sperm cells



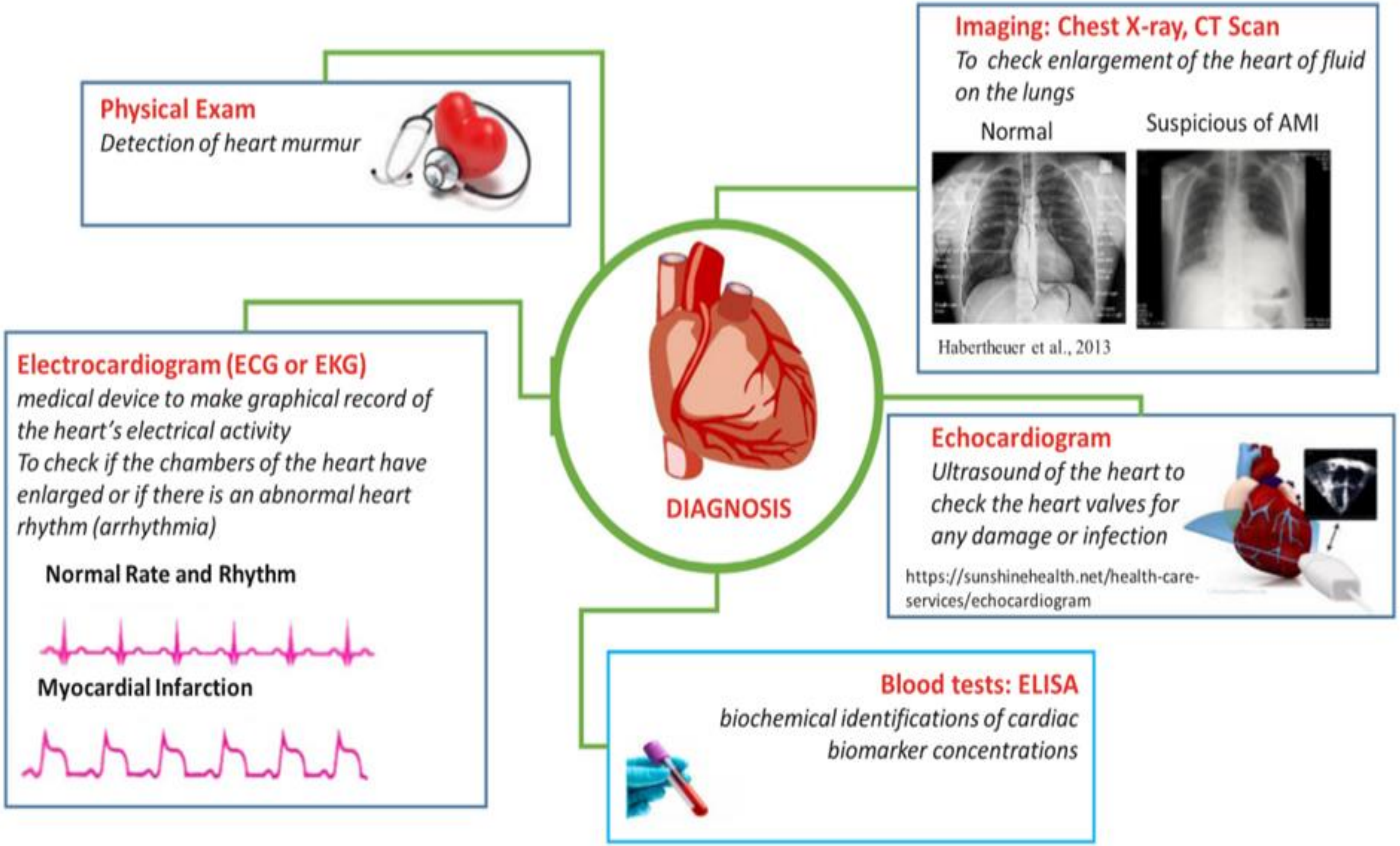


SAW-based Biosensors



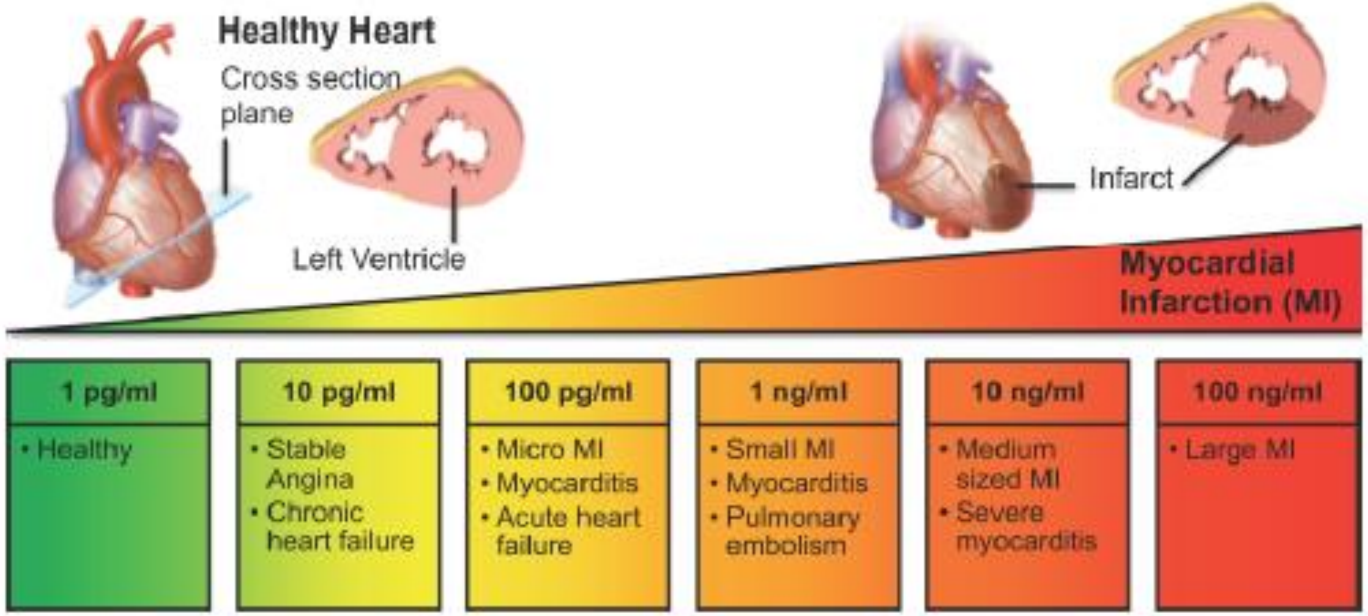
Y. Zhang et al., *Analyst* 2017

SAW-Biosensor for Detection of Cardiac Troponin I

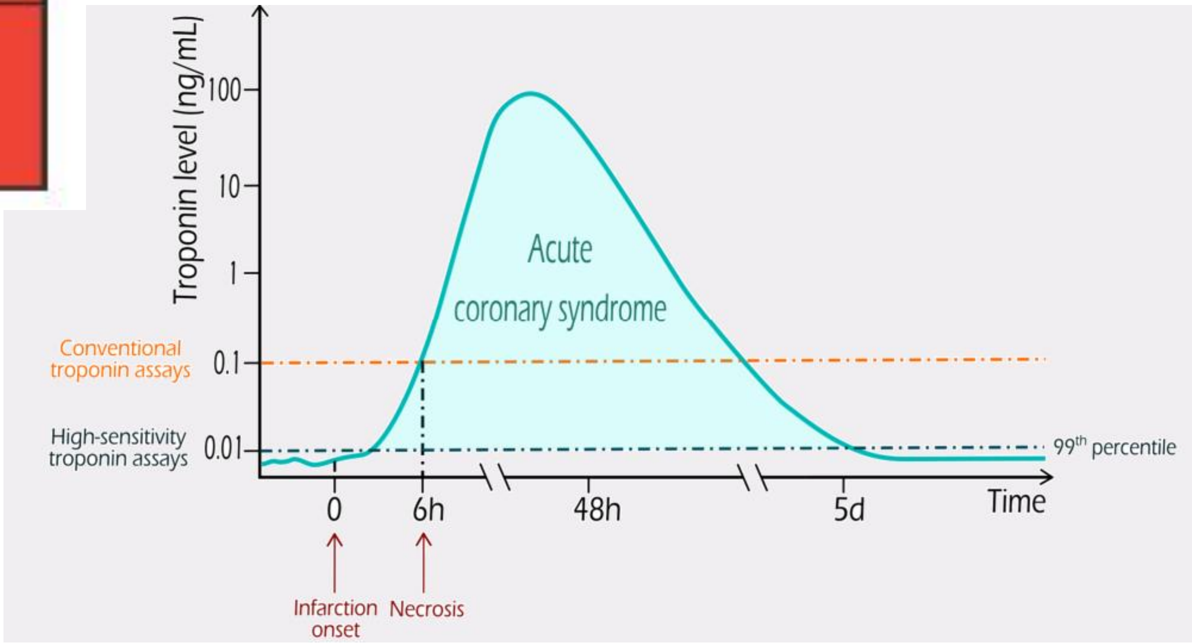


S. Szuneritsa.et al., *Biosensors and Bioelectronics*, 2019

SAW-Biosensor for the Detection of Cardiac Troponin I

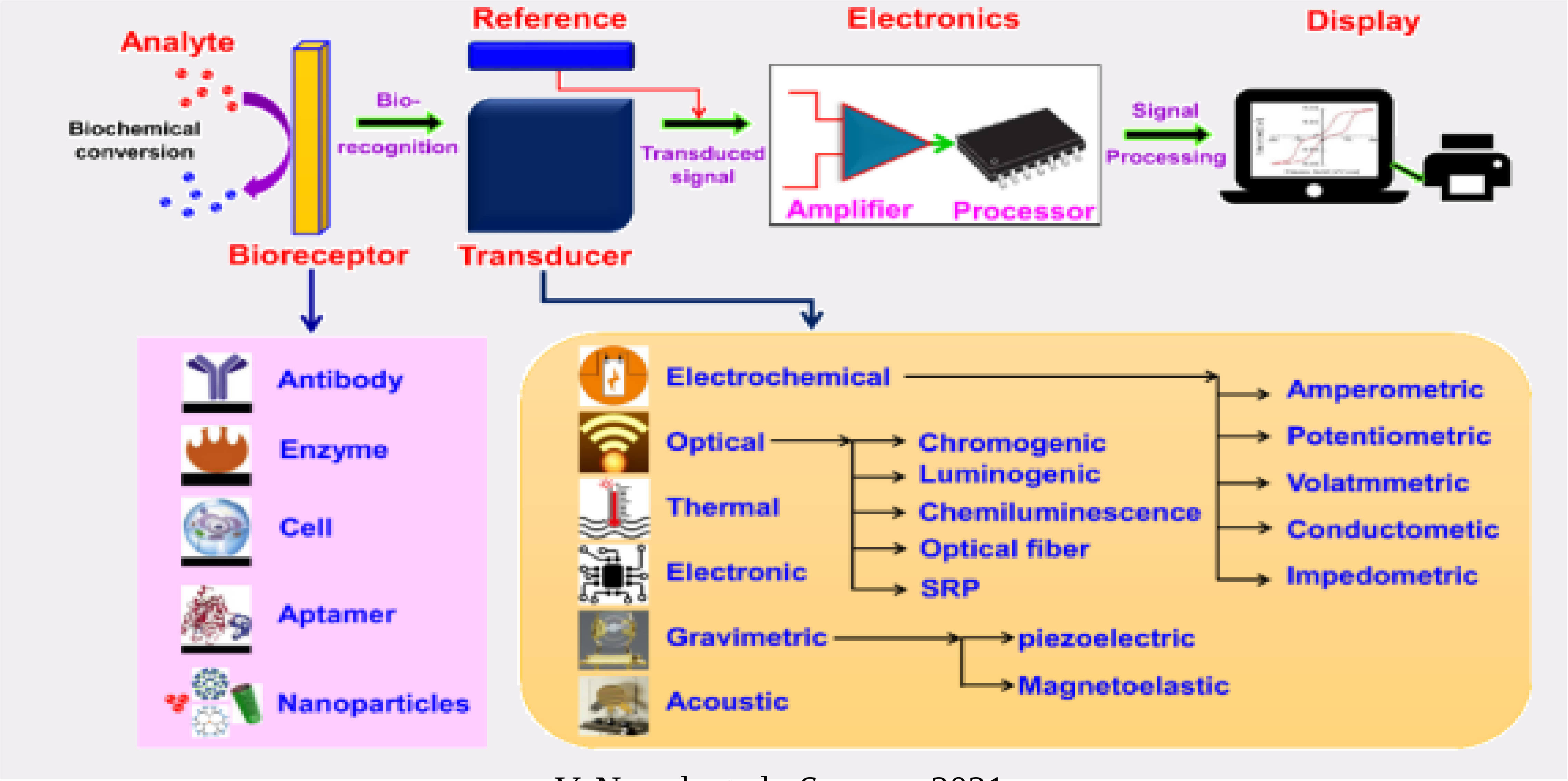


cTnI in healthy humans: lower than 0.04 ng mL^{-1}
increased risk for acute heart failure: around 0.1 ng mL^{-1}



M. Savonnet.et al., *Pharmaceutical and Biomedical Analysis*, 2020

SAW-Biosensor for the Detection of Cardiac Troponin I



V. Naresh et al., *Sensors*, 2021

SAW-Biosensor for the Detection of Cardiac Troponin I

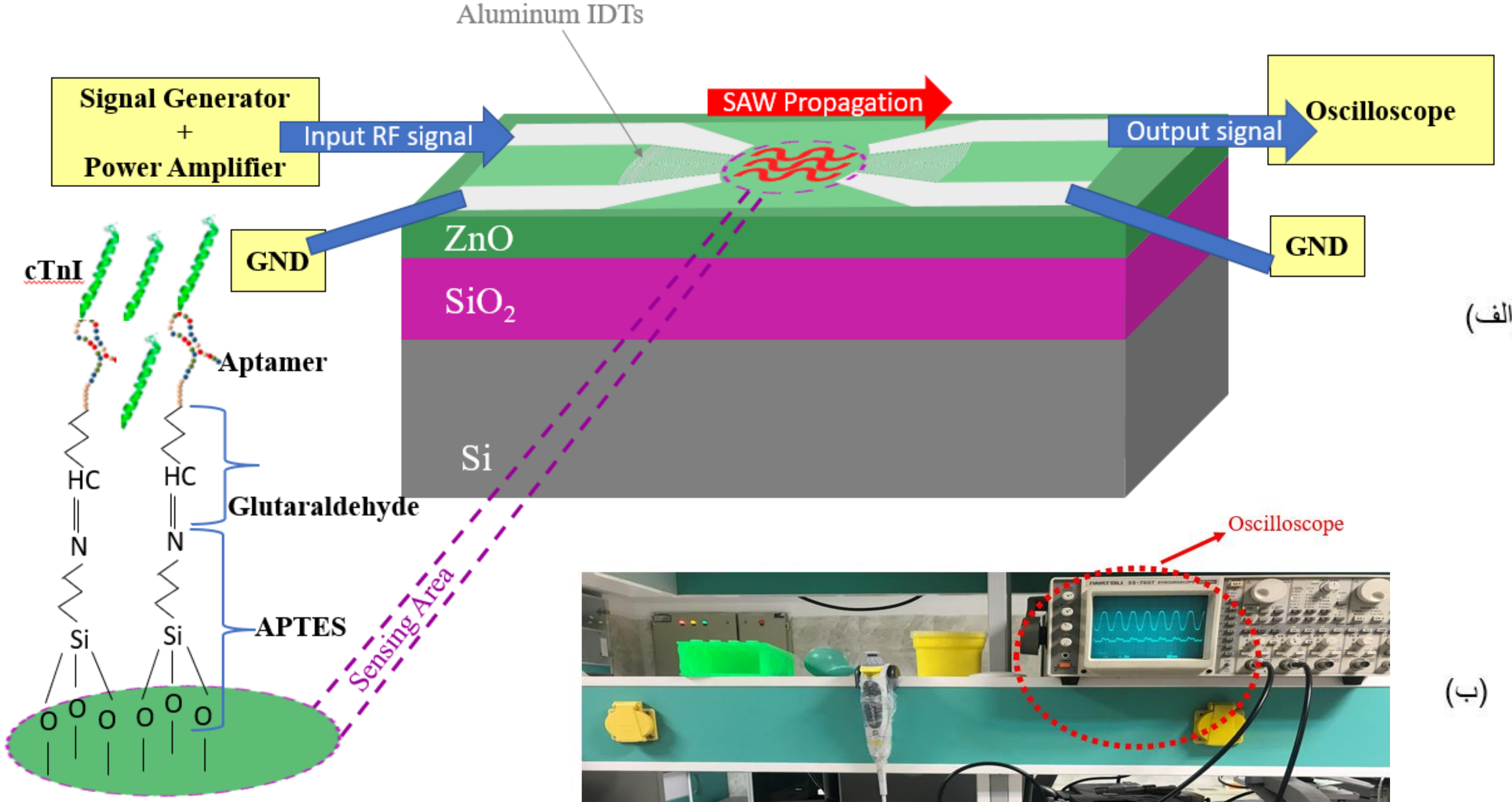
Features	Antibody	Aptamer
Specificity	High	High
Size	Relatively high	Small
Stability	Unstable	Stable
Affinity	High	High
Immunogenicity	High	No humoral response
Potential target	Immunogenic molecules	Any target
Production	In vivo	In vitro
Cost	Expensive	Relatively cheap
Modification	Limited	Almost unlimited
Time to generate	~6 months	~3–7 weeks
Renal separation	Slow	Fast

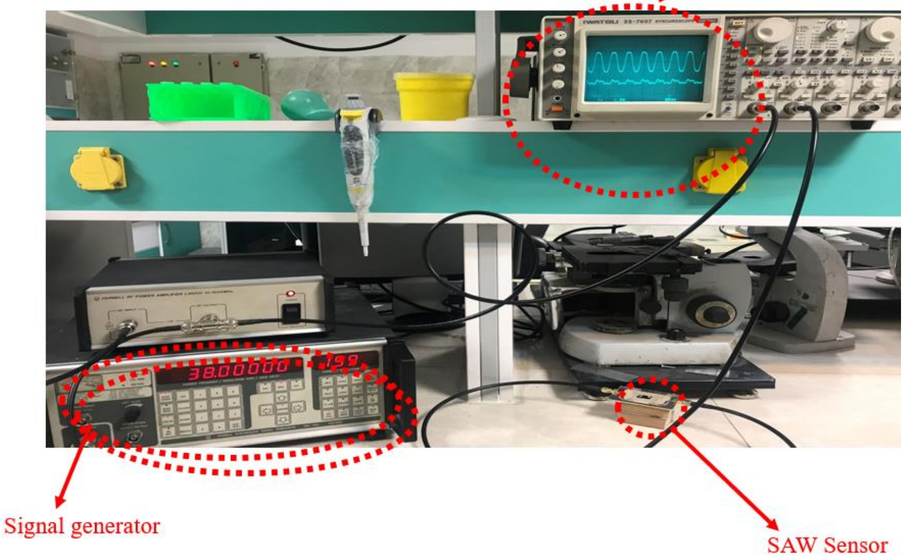
V. Subjakova.et al., *Polymers* 13, 2021

Sequence (5′ to 3′)	K_d value (cTnI)	K_d value (Troponin complex)
TCACACCCTCCCTCCCACATACCGCATACACTTTCTGATT	3.41 nM	3.12 nM
CCCGACCACGTCCCTGCCCTTTCCTAACCTGTTTGTTGAT	1.13 nM	4.47 nM
ATGCGTTGAACCCTCCTGACCGTTTATCACATACTCCAGA	1.14 nM	5.70 nM
CGTGCAGTACGCCAACCTTTCTCATGCGCTGCCCCTCTTA	270 pM	3.10 nM
CAACTGTAATGTACCCTCCTCGATCACGCACCACTTGCAT	3.25 nM	10.61 nM
CGCATGCCAAACGTTGCCTCATAGTTCCCTCCCCGTGTCC	317 pM	3.37 nM

H. Jo.et al., *Analytical chemistry*, 2015

SAW-Biosensor for the Detection of Cardiac Troponin I





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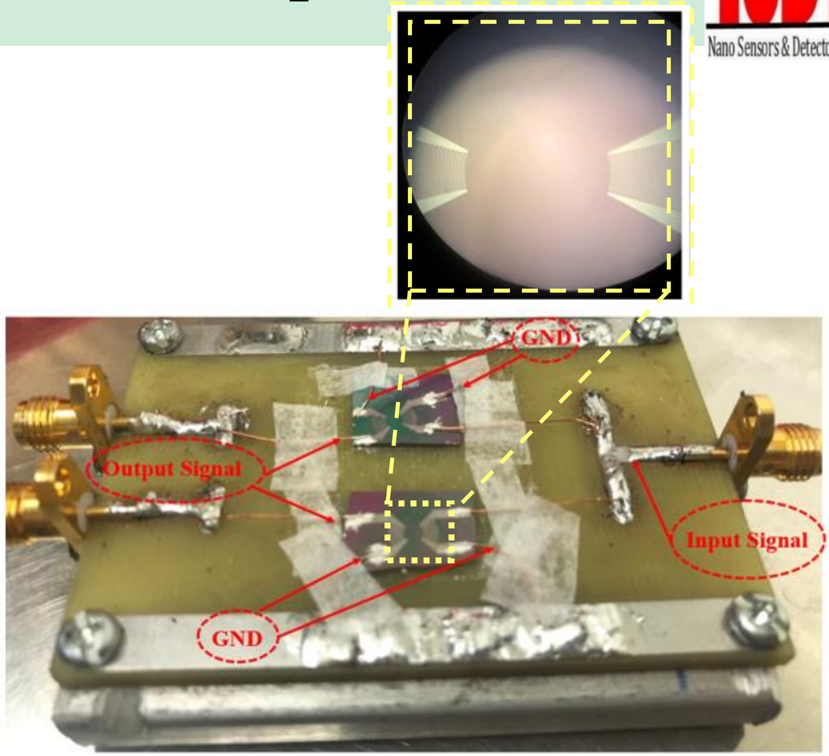

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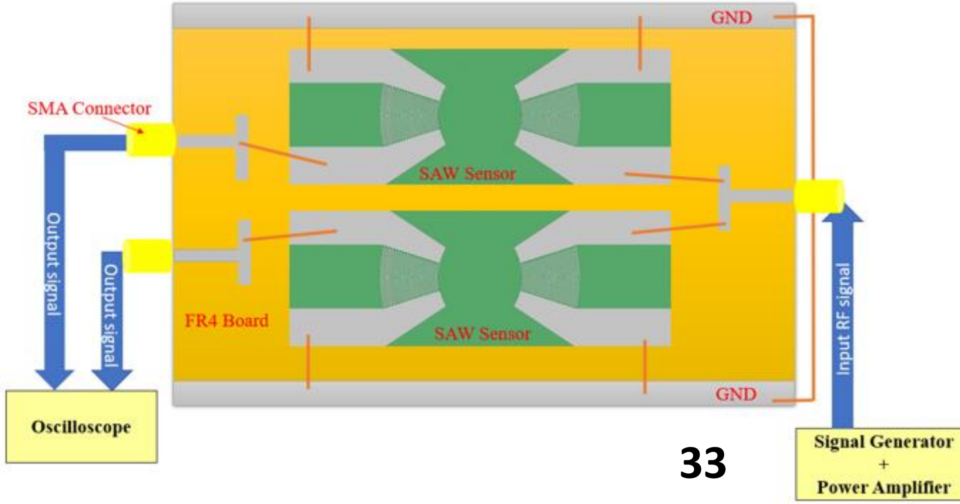


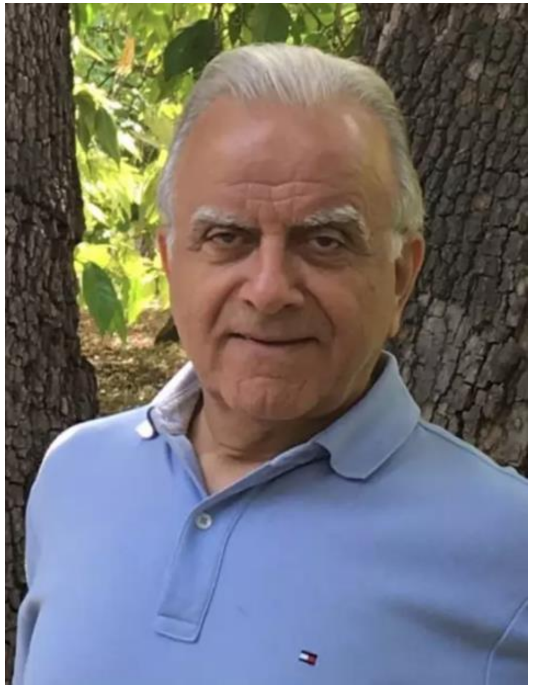
Conclusion

The Proposed tweezers based on SAWs are promising for:

- Application in efficient and compact Lab-on-Chip systems
- Realizing locally reinforced particle manipulation
- Manipulation of sub-wavelength small particles
- Label-free manipulation of target particles
- High potential for novel and enhanced functionalities by introducing metasurfaces in the active zone of the channel.

Special Thanks to Bio-Acoustics group members

Thanks to my Bio-Acoustics Academic collaborators



Dr. Mohammad-Kazem Moravvej,
Faculty of Electrical and
Computer Engineering, TMU,
Iran

Dr. Mohammad Zabetian,
Faculty of Mechanical
Engineering, TMU, Iran

Dr. Iman Halvaei
Faculty of Medical Sciences,
TMU, Iran

Dr. Reza Nosrati
Department of Mechanical
Engineering, Monash University,
Austria

Thanks for your attention