Electromagnetically Actuated Ball Valve Micropumps

presented by

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and

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Outline

1. Lab-On-a-Chip
2. State-of-the-art

Working principle

1. External electromagnet
2. Multi-layered microchip
Microfabrication
- Magnetic membrane
- PMMA microchip
- Glass microchip

Results & discussion
- Magnetic membrane actuation
- Micropumps characterization
- Damped oscillator model

Conclusion
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1. Lab-On-a-Chip
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Working principle

- External electromagnet
- Multi-layered microchip
Lab-On-a-Chip:

- Microfluidic Laboratory on a chip
- Plastic / glass material

Need for **low-cost** micropumps targeted to biochemical applications:

- **disposable** or **sterilizable**
- with possible **integration** in Lab-On-a-Chip devices
Main aspects to take into consideration in the conception of a micropump:
State-of-the-art (rapid overview)

Microvalves

Injection moulded ball valve fabricated with LIGA technology
IMM Main (Internet website, 1996)

Electromagnetic active ball valve
O. Krusemark
Electromagnetic actuation:

- simplicity
- force magnitude
- deflection amplitude

× miniaturization  but  ✓ external actuation
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   Multi-layered microchip

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   PMMA microchip
   Glass microchip
Working principle ▶ External electromagnet

Pumping principle:

- Reciprocating **diaphragm** ("positive displacement" pump)
- Use of passive **ball valves**
- **External** electromagnetic actuation

4800 turns coil
(Atam windings s.r.l.)
Working principle → Multi-layered microchip

Fabrication method based on **powder blasting** erosion process.

**Plastic** device (polymethylmethacrylate)

**Glass** device (borosilicate)
Working principle
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Integration of a \textit{magnetic material} into the \textit{flexible diaphragm} of the reciprocating micropump.

\textbf{PDMS with NdFeB powder}
(MQP-S-11-9 powder, Magnequench)

\textbf{PDMS + NdFeB commercial magnet}
Fabrication of the **composite magnet**:

PDMS matrix + NdFeB powder (typical size ~50 µm)  
→ Optimal powder ratio: ~ 50% vol. powder

**MQP-S-11-9 powder datasheet:**
- **median size**: 35 - 55 µm
- **distribution width**: 10 - 30 µm
- **apparent density**: 3.6 - 4.2 g/cm³
- **theoretical density**: 7.43 g/cm³
Microfabrication - Powder blasting

Microstructuration of microfluidic chips by powder blasting

- nozzle
- pressurized abrasive powder (1-5 bar)
- distance to the substrate
- Al₂O₃ powder (average size 30 µm)
- mask layer
- sample X-Y translation
- substrate
Microfabrication ▶ Powder blasting

Microstructuration of microfluidic chips by **powder blasting**

Apparent roughness: ~1 µm
Small relative roughness → *hydraulically smooth* microchannels

**SEM photograph of a PMMA microchannel fabricated by powder blasting**

100µm wide channel
30 µm Al₂O₃ particles

**Photograph of a glass microchannel fabricated by powder blasting**

1 mm scale bar
Microfabrication ▶ PMMA microchip

Fabrication process of the PMMA microchip

- Metallic mask cut by Nd:YAG laser
- Structured PMMA sheet
- Channel width: 500 µm *
- Thickness: 250 µm
  - Typical: 100 µm → 500 µm
- Powder blasting (Al₂O₃ particles)
- CAD files
- triethylene glycol dimethacrylate bonding solution applied on each layer
- 5 min @ 70 °C
- Final Microfluidic chip
- 36mm x 22mm x 5mm (without connectors)
Microfabrication  ➤ Glass microchip

Fabrication process of the **glass** microchip

- **Powder blasting** of mask protected **borosilicate** glass (borofloat 33, *Schott*)
- Cleaning (isopropanol + piranha solution)
- Glass **fusion bonding** at 600 °C

- Membrane assembly: **PDMS/glass** bonding (plasma treatment)
- Connectors gluing: epoxy (Epo-tek)
Microfabrication ➤ Glass microchip

Powder blasting of holes in glass material

1. without 2nd impact effect
2. 2nd impact effect

- Evolution of the erosion profile of a 1 mm thick borosilicate hole
- Time evolution of the erosion depth (after P.J. Slikkerveer et al.)

- appropriate shape for a ball valve seat
Microfabrication  ▶ Glass microchip

Glass prototype of the electromagnetically actuated ball valve micropump

ext. dim. 36 mm × 22 mm

Photograph of the integrated ball valve fabricated in glass

steel ball: Ø 0.7 mm
Microfabrication
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- PMMA microchip
- Glass microchip

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Conclusion
Characterization of the magnetic actuator

→ Force as a function of the air gap, for different currents (DC) in the coil.

Force max.: ~ 0.5 N
(100 mA DC current)
Results & discussion  ▶ Magnetic membrane actuation

Measurement of the membrane stiffness

Measured stiffness: $K \sim 700 \text{ N/m}$
Characterization of the ball valve (glass device)

Efficiency of the valve:

\[ \varepsilon = \frac{Q_+(P)}{Q_-(P)} \approx \frac{20 \text{ mL/min}}{0.25 \text{ mL/min}} = 80 \]

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Ball valve integrated in a glass microchip

**steel ball : Ø 0.7 mm**

Electromagnetically Actuated Ball Valve Micropumps

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Results & discussion

Ball valve micropumps

Characterization of the ball valve micropumps
(glass + PMMA device)

Flow rate – back-pressure characteristic of the ball valve micropump in glass

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Results & discussion  

Damped oscillator model

Equivalence with electrical circuit (RLC electrical model)

Resistance: \[ R = \frac{128 \mu l}{\pi D_H^4} \]

Inductance: \[ L = \frac{\rho l}{S} \]

Capacitance: \[ C = \frac{AV}{\Delta p} \]

Liquid flow in microchannels  

Membrane
Results & discussion ▶ Damped oscillator model

Equivalence with electrical circuit (RLC electrical model)

Reciprocating pump with ideal valves:

\[ f_0 = \frac{1}{2\pi} \sqrt{\frac{K}{\left(\frac{A}{a}\right)^2 m}} \]

Equivalent electrical model of the reciprocating pump

\[ f_0 = \frac{1}{2\pi} \sqrt{\frac{1}{LC}} \]
Results & discussion

Damped oscillator model

Equivalence with electrical circuit (RLC electrical model)

→ Good estimation of the resonance frequency with this hydrodynamic model of the ball valve reciprocating micropump.

Flow rate – frequency characteristics of the ball valve micropumps

![Graph showing flow rate vs. frequency for different micropumps](image)

100 mA sinusoidal actuation:
- Glass ball valve micropump
- PMMA ball valve micropump
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Conclusion
Conclusion

Summary of the performances of the different prototypes:

<table>
<thead>
<tr>
<th>Pump type (ball valve micropump)</th>
<th>Maximum back-pressure</th>
<th>Maximum water flow rate</th>
<th>Typical operating frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMMA</td>
<td>225 mbar</td>
<td>~ 5 mL/min</td>
<td>f₀ ~ 30 – 40 Hz</td>
</tr>
<tr>
<td>Glass</td>
<td>280 mbar</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Main results:

• Flexible membrane → high compression ratio (bubble tolerance & self-priming)
• ball valve → high efficiency (limited reverse flow)
• External electromagnetic actuation → high forces achievable
Thank you!