FPNI Ph.D. Symposium on Fluid Power

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HARBIN INSTITUTE OF TECHNOLOGY

Pneumatic Control microfluidic systems and applications

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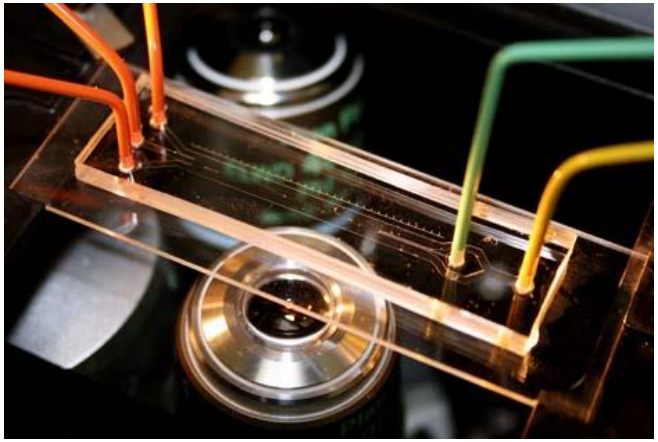
Contents

1 Background



Chip size: several cm^2

Micro-channel network

Controllable fluidic system

All kinds of functions

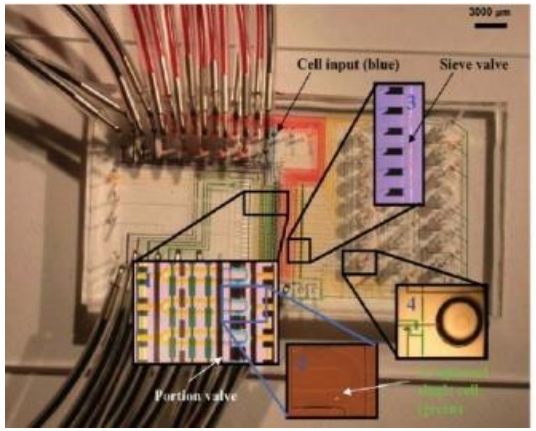
Chemical reaction, biomedical analysis

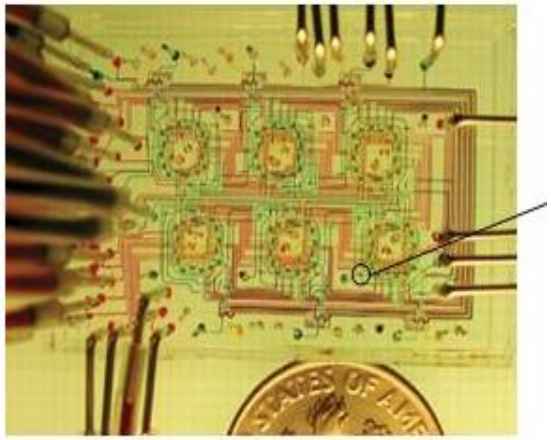
Drug delivery

Lab on a chip

1 Background

Pneumatic microfluidic chips



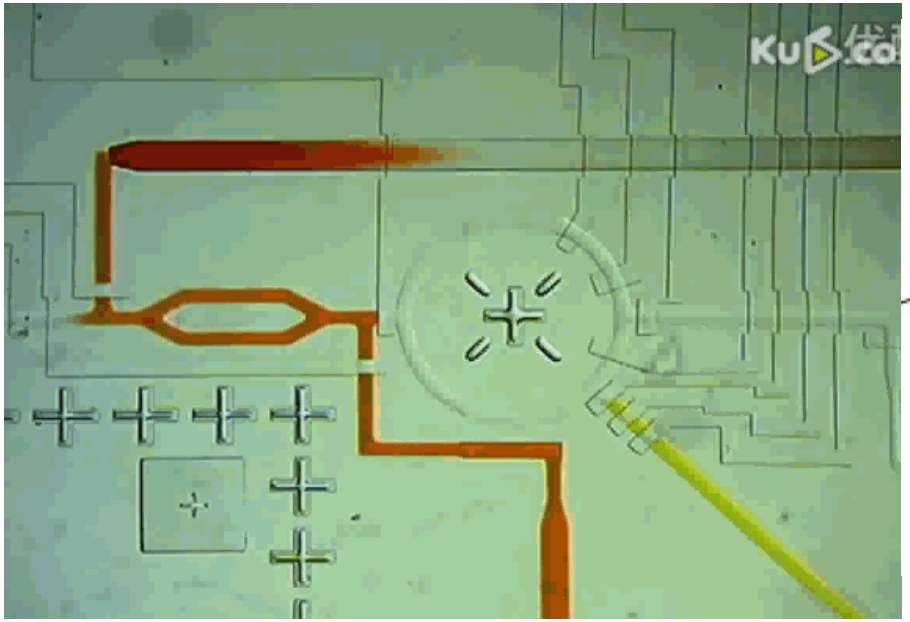


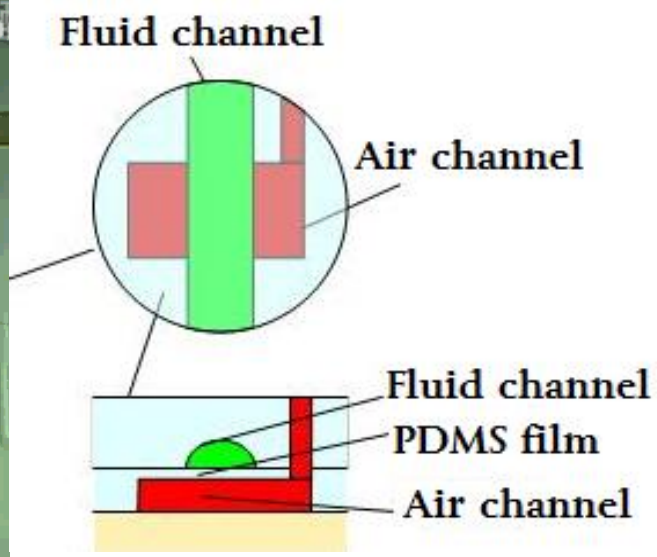
large scale integrated pneumatic microfluidic chips

Quake's Group, Stanford University, 2000

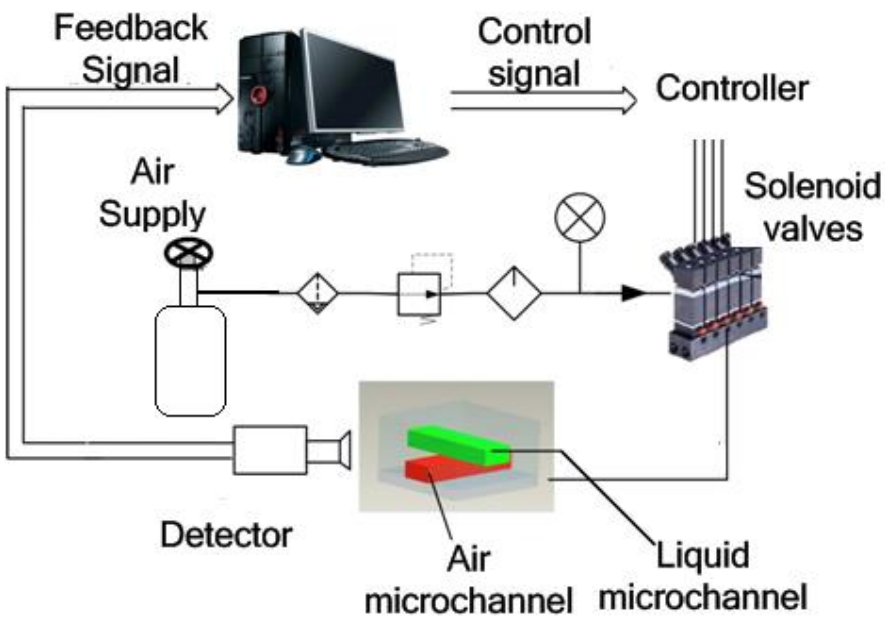
Large scale integrations with hundreds pneumatic micro valves and actuators

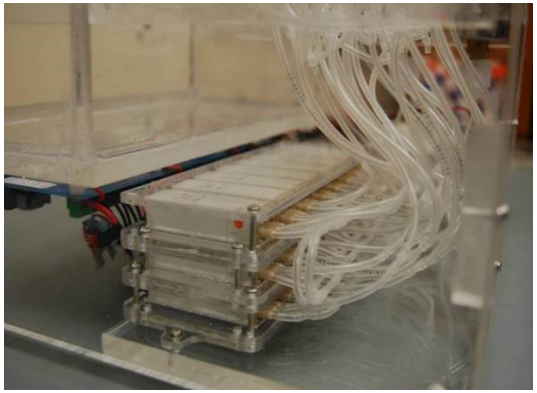
1 Background





1 Background





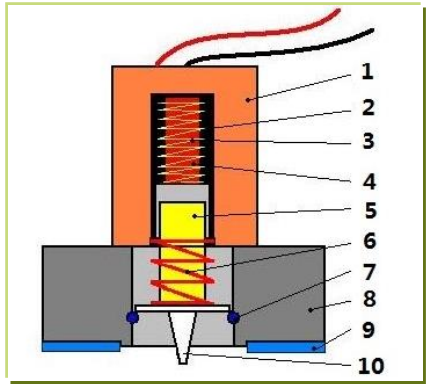
Schematic of a pneumatic actuated multi-layer microfluidic chip with its pneumatic supporting systems

To make the off-chip supporting devices smaller, portable and easily to be integrated with the chips

Prof. Whitesides, Harvard University

2 Pneumatic off-chip valves

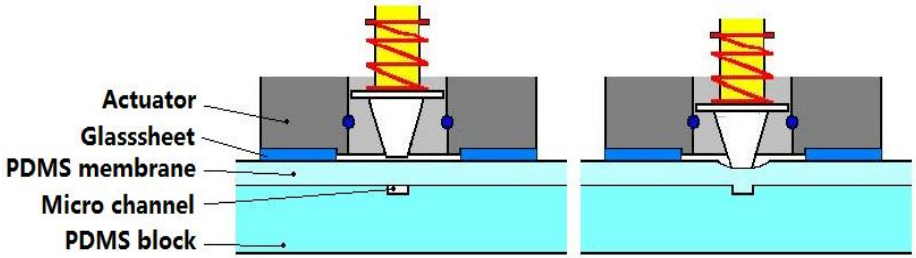
PDMS valve body + low cost actuation



Schematic design of the electromagnetic actuator (a), 1.plastic housing; 2. ferromagnetic shell; 3.coil; 4=static iron; 5.moving iron; 6.return spring; 7.positioning pins; 8.fixing device; 9.glass slide; 10.valve core.

Advantages:

- PDMS valve body, smaller friction force on the spool
- Better sealing
- Better to be linked with the chip
- Rapid prototyping



Schematic design of the microvalve in open state (left) and closed state (right)

2 Pneumatic off-chip valves

PDMS	Property	Consequence
Optical transparent	UV cutoff 240 nm	Optical detection: 240 – 1100 nm
electrical insulating	Breakdown voltage $2x10^7$ V/m	Allow embeded circuits
Mechanical	Elastomeric	Allow actuation by reversible deformation
Thermal insulating	0.2 W/(m•K) Thermal expansion: 310 μm/(m• °C)	Thermal insulator Hard to release heat from electrophoresis
Interfacial	low surface free energy 20 erg/cm^2	Easy to seal and adhere to other materials
Permeability	Impermeable to liquid water, but permeable to gases	Can handle liquid solution inside channels, allow gas transport
Reactivity	Inert, but can be oxidized by exposure to plasma	Not reactive to most reagents Surface modifiable
Toxicity	Non-toxic	Can be implanted and work with living organisms

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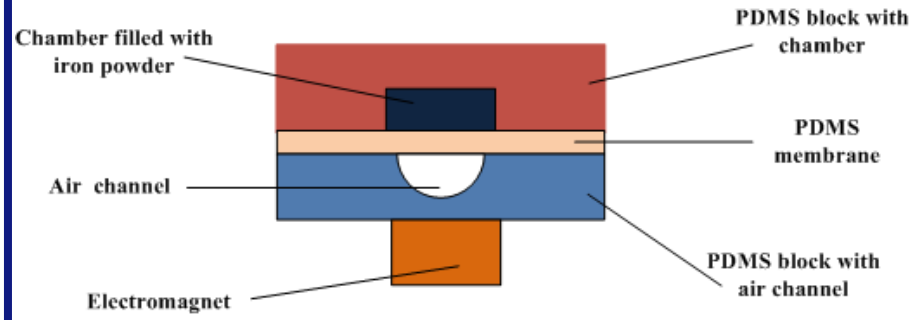
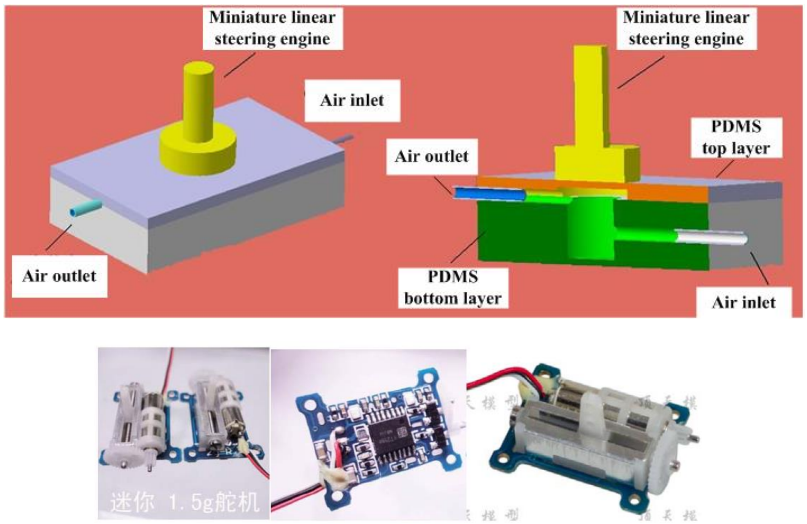
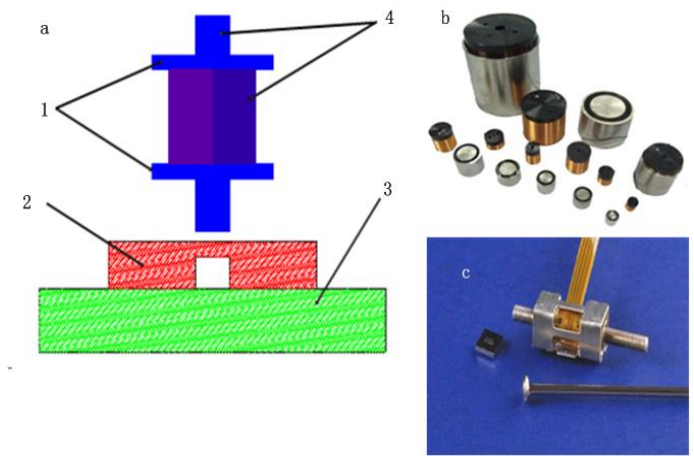
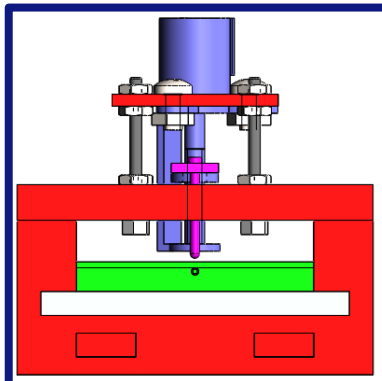
2 Pneumatic off-chip valves

Driving methods of the PDMS pneumatic off-chip valve

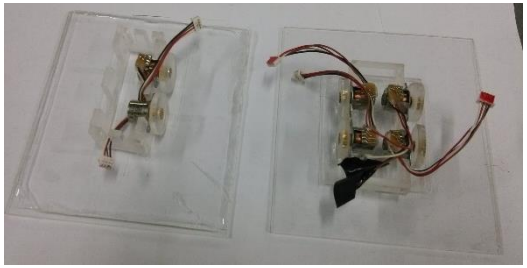




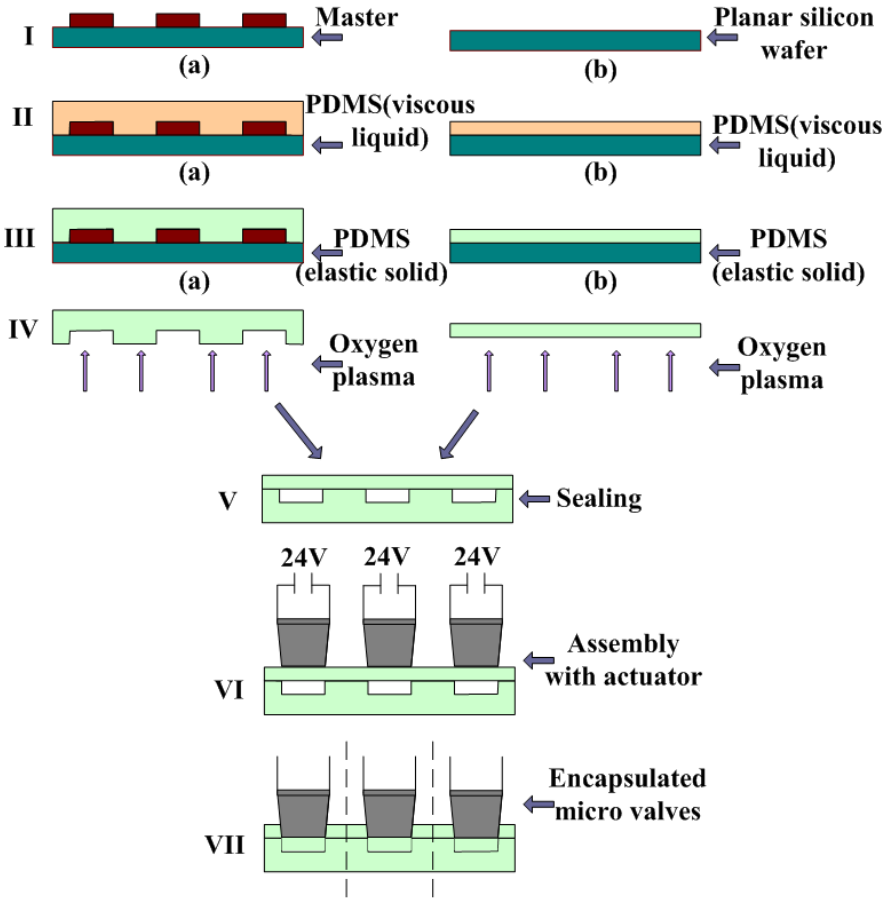




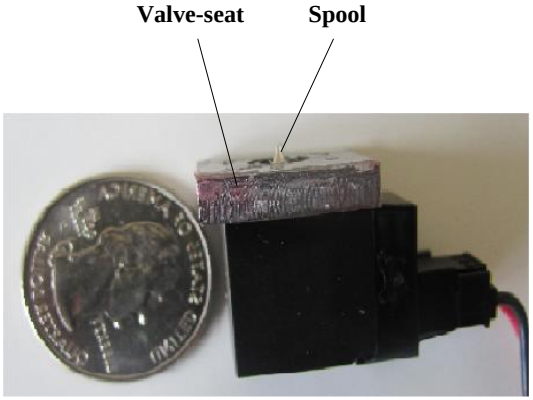
Micro stepper motor



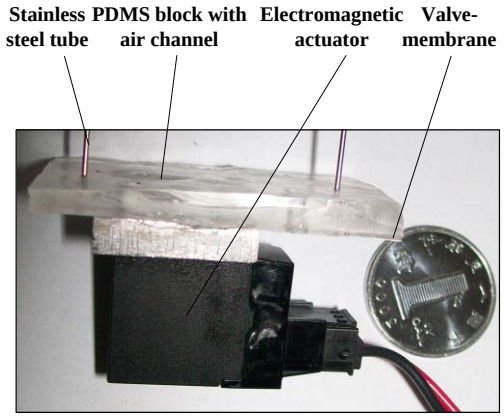
2 Pneumatic off-chip valves



Fabrication of the off-chip valve-soft lithography



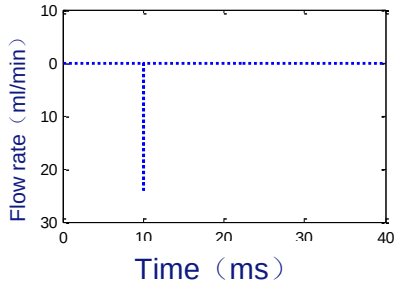
The packaged Electromagnetic actuator



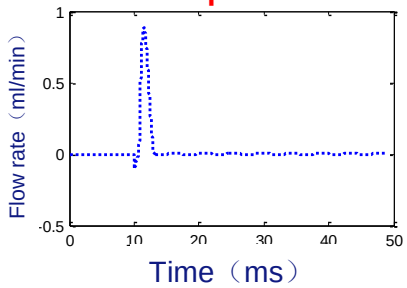
The packaged the off-chip valve

2 Pneumatic off-chip valves

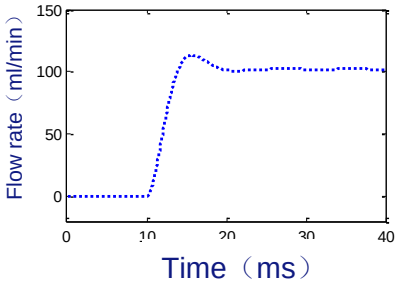
Simulation results of the off-chip microvalve



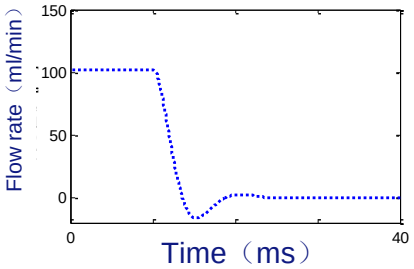
Back electromotive voltage



Spool actuated force

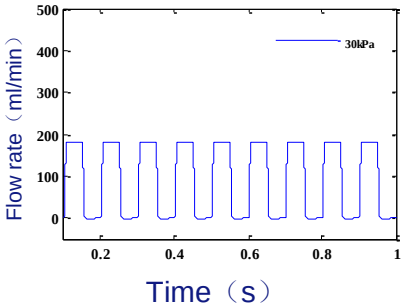


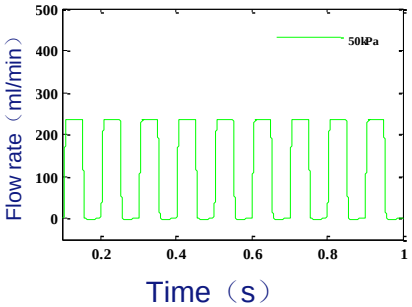
Spool pull dynamic response

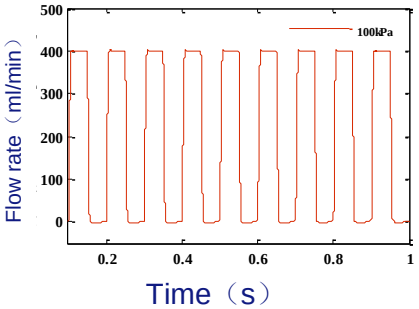


Spool release dynamic response

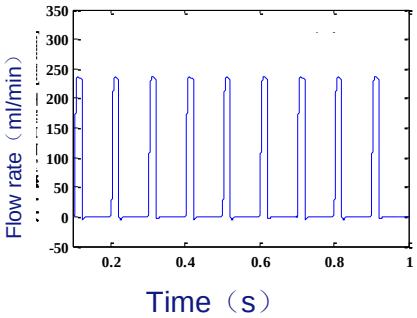
Outlet flow rate of the off-chip micrvalve under different pressures

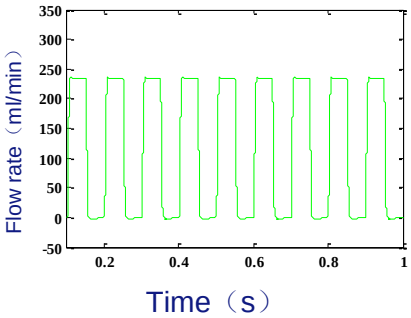


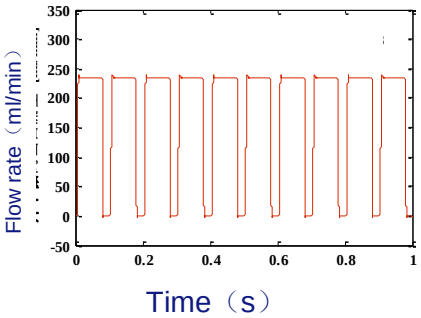




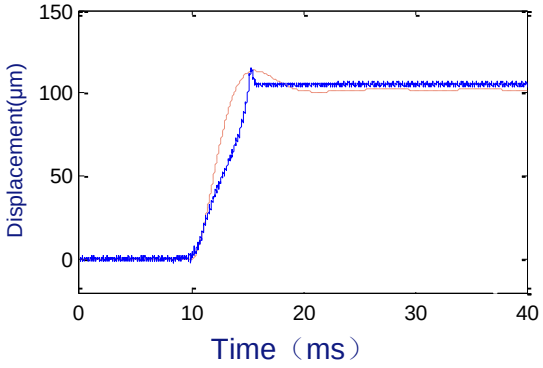
Outlet flow rate of the off-chip micrvalve under different duty cycles

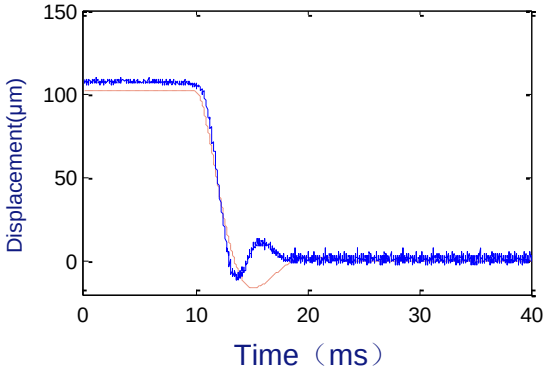




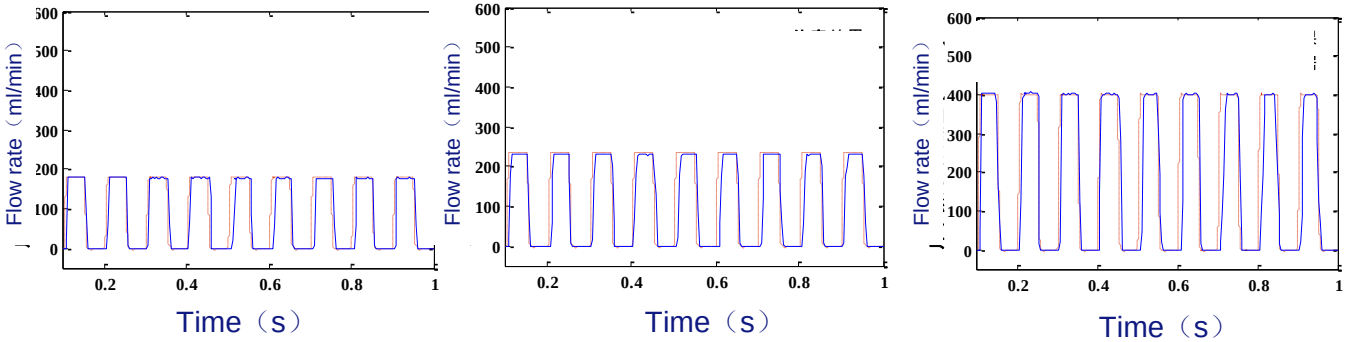


2 Pneumatic off-chip valves

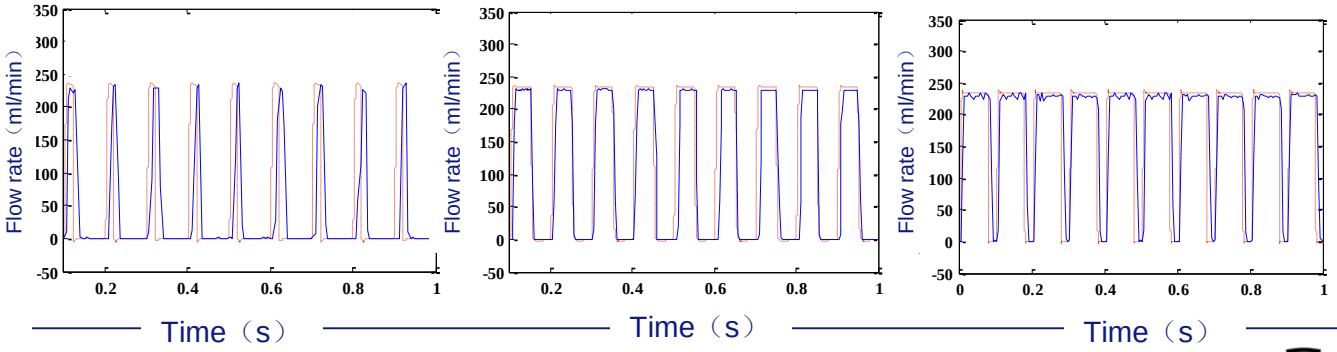




Testing schematic diagram and response time experimental results of the electromagnetic microvalve



Comparison between experimental data about outlet flow of the off-chip micrvalve under different pressures and simulation results



Comparison between experimental data about outlet flow of the off-chip micrvalve under different duty cycles and simulation results

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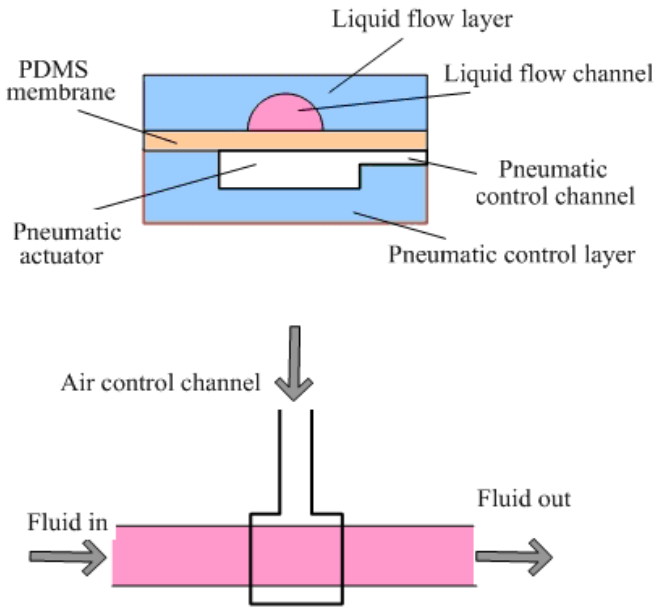
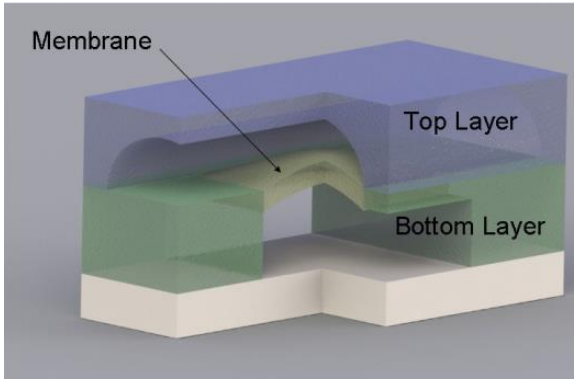
3 Pneumatic microvalve and system

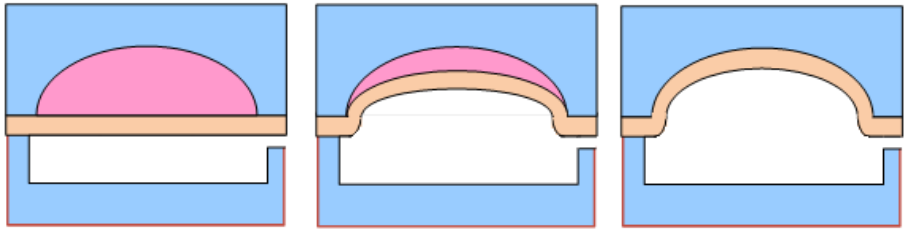
Structure and working principle of the on-chip microvalve



Schematic of one membrane microvalve with a pneumatic actuator



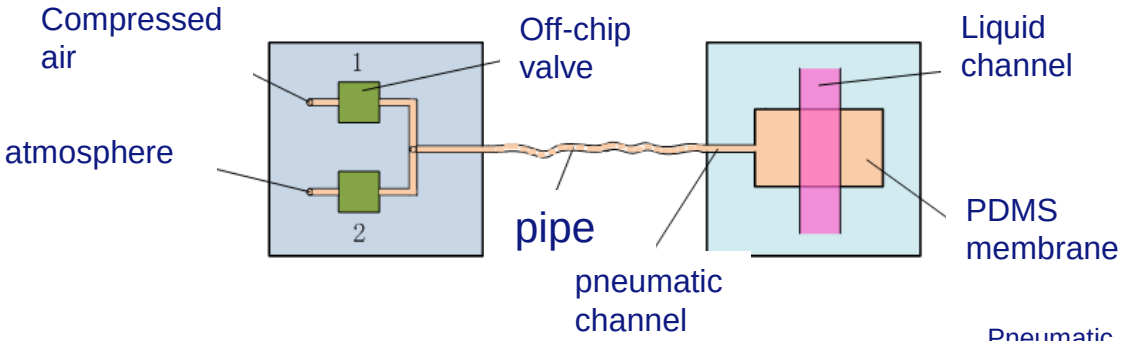
Three-dimensional structure view



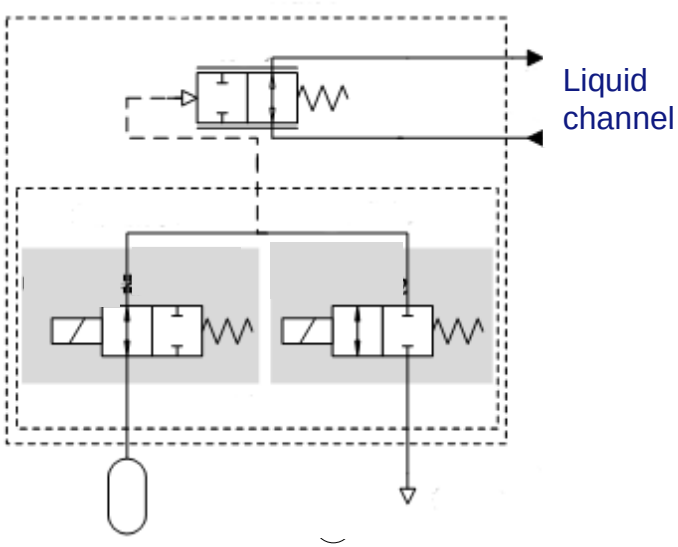
Schematic diagrams in Fully open/ partially open/ fully closed state of the membrane microvalve

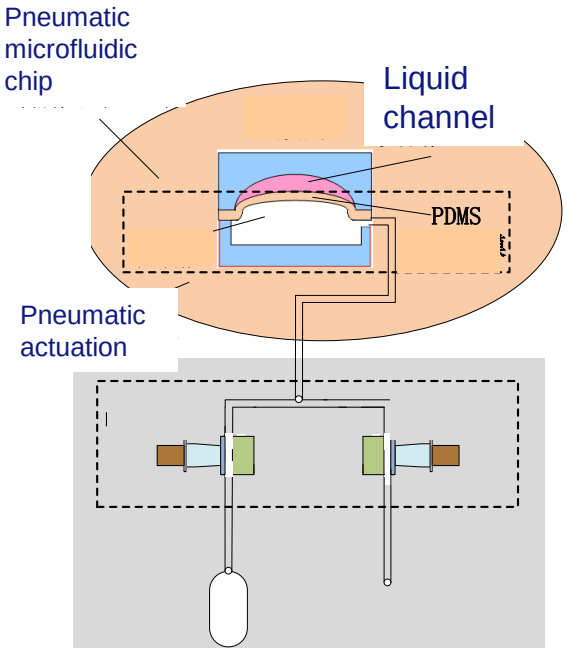
3 Pneumatic microvalve and system

Structure of the PDMS pneumatic pressure driven microvalve



PDMS pneumatic pressure driven microvalve and the system

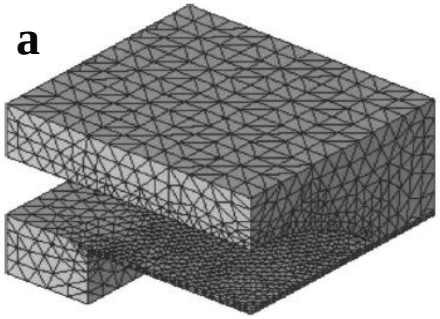




3.2 Multi-physical fields coupling mechanism and mathematic models research

PDMS actuated membrane deflection mathematic model and characteristics analysis

a



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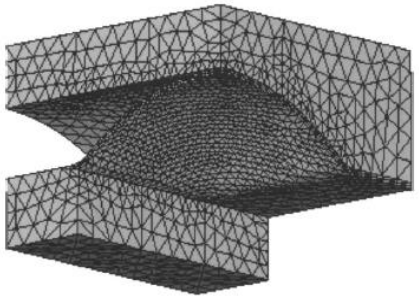
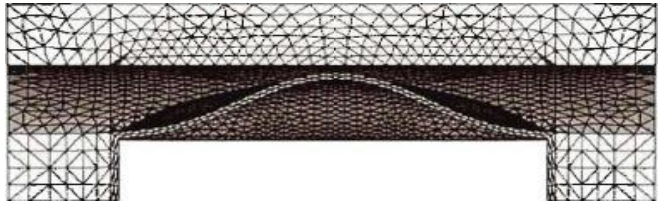


c



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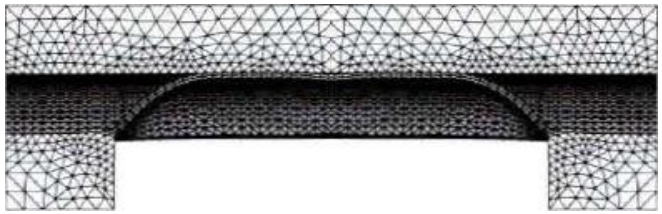

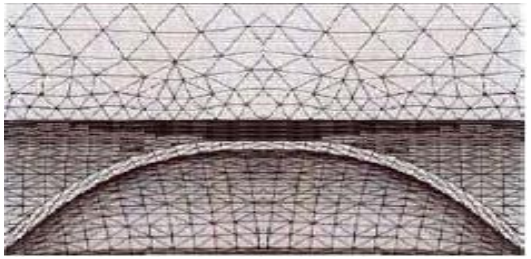

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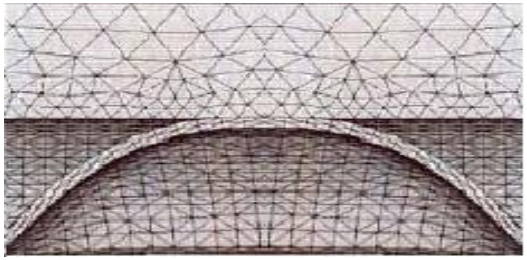


f

(a) Undeformed configuration of 1/4 structure; (b) Deformed configuration of 1/4 structure; (c) Cross-sectional view ($p_{md} < p_{close}$); (d) Cross-sectional view ($p_{md} \geq p_{close}$); (e) Longitudinal sectional view ($p_{md} = p_{close}$); (f) Longitudinal sectional view ($p_{md} > p_{close}$).

$$\delta_{max} = \frac{w_m}{4}\left[\frac{3p_{md}w_m(1-v_m^{\ 2})}{Eh_m}\right]^{\frac{1}{3}}$$

$$V_m = \frac{2l_m w_m \delta_{max}}{3}$$

conclusion：

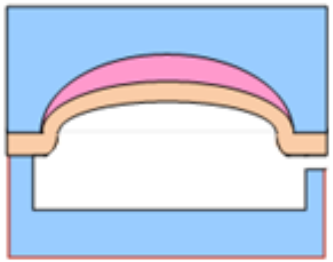
1.Large deformation theory;

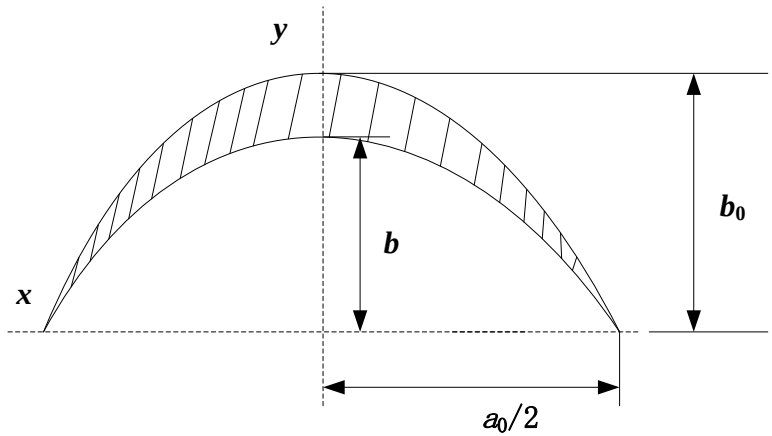
2.Nonlinear characteristics;

3.Uniform deformation in length.

3 Pneumatic microvalve and system

Flow rate mathematical model of the on-chip microvalve under different valve-openings and calculation analysis





Size of the valve port of the on-chip microvalve

Cross-section area

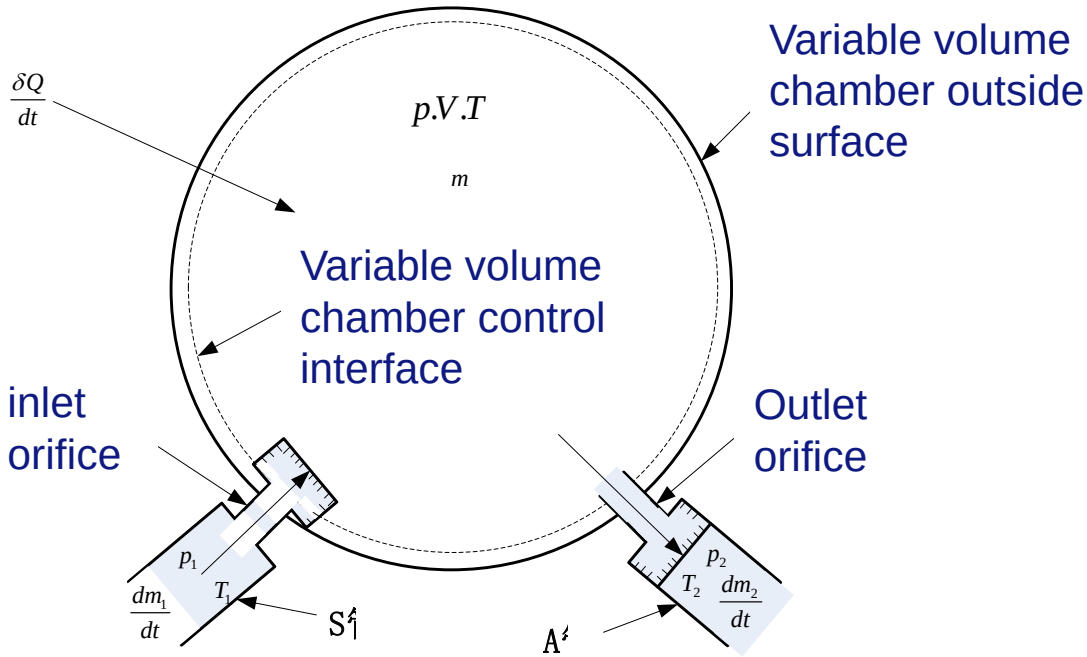
$$A=\frac{2a}{3}(b-b_0)$$

$$q=C_d A\sqrt{\frac{2\Delta P}{\rho}}$$

Theoretical calculated liquid flow rate with different valve-openings of the on-chip microvalve (μL/min)

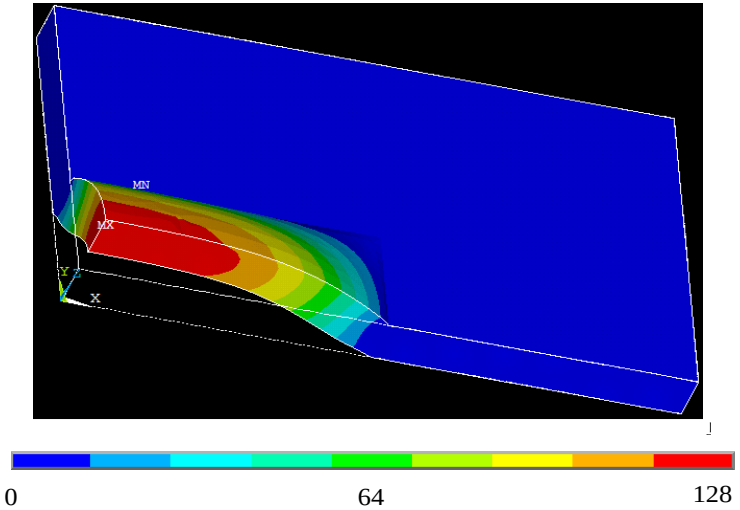
Driven liquid pressure kPa / Pneumatic pressure kPa	10	20	30
0	2.05×10^3	1.85×10^3	1.72×10^3
10	1.87×10^3	2.89×10^3	2.26×10^3
20	2.13×10^3	3.74×10^3	3.54×10^3
30	1.62×10^3	3.01×10^3	5.61×10^3
40	1.14×10^3	2.26×10^3	3.69×10^3
50	0.69×10^3	1.61×10^3	2.80×10^3
60	0.30×10^3	0.98×10^3	1.97×10^3
70	0	0.42×10^3	1.20×10^3
80	0	0	0.52×10^3
90	0	0	0

3 Pneumatic microvalve and system

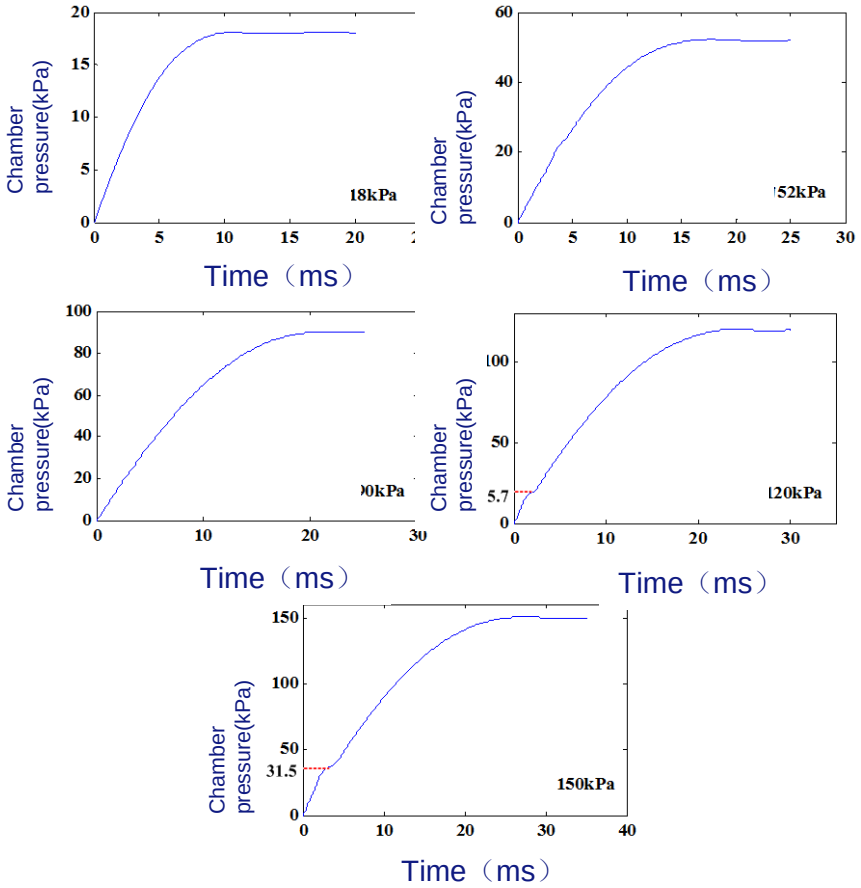


Model of the actuated chamber with variable volume

3 Pneumatic microvalve and system



The actuated PDMS membrane deformation under 100kPa

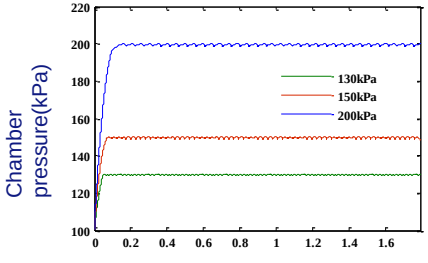


Numerical calculation results of response time for TBC under different pressures, the initial differential pressure is 10kPa, 52kPa, 90kPa, 120kPa, 150kPa, separately

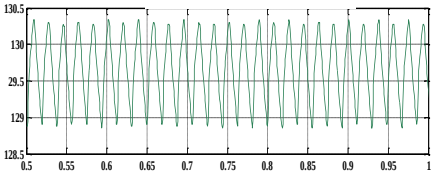
3 Pneumatic microvalve and system

Bang-Bang controller: Set two control limit values

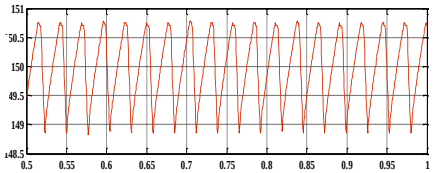
$$u(k)=\begin{cases}0 & e(k)<E_{\min}\\ 1 & e(k)>E_{\max}\end{cases}$$



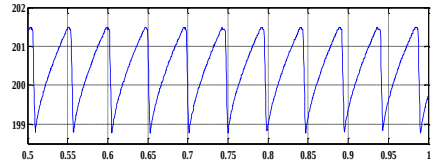
130kPa



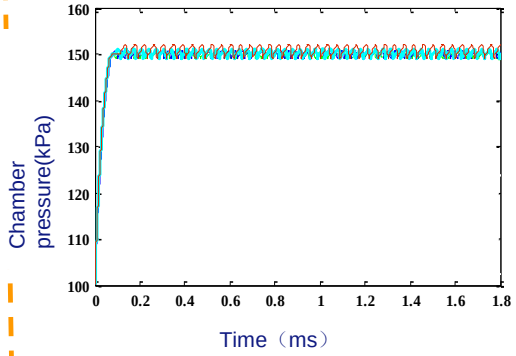
150kPa



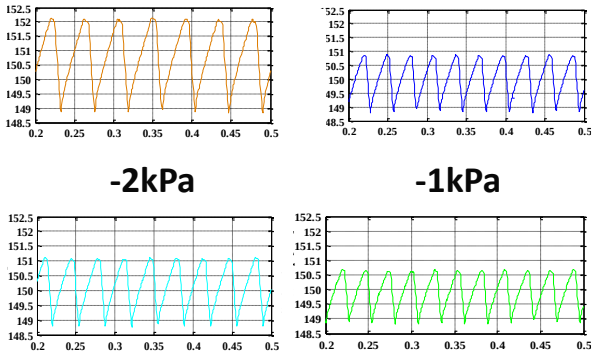
200kPa



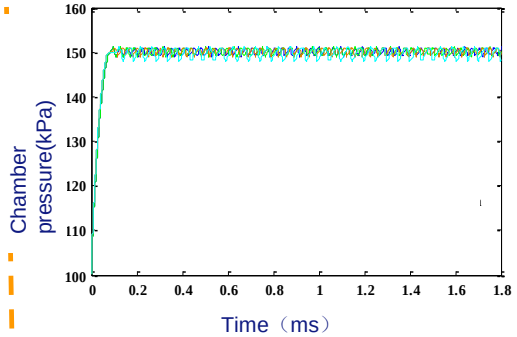
Step response process of the actuator under different inlet pressures



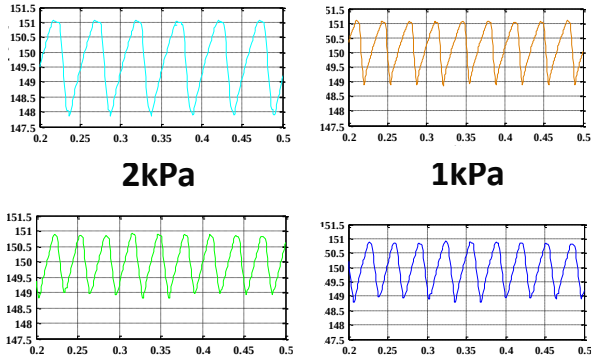
Step response process under different Bang-Bang lower thresholds



-2kPa -1kPa -0.5kPa 0kPa



Step response process under different Bang-Bang super thresholds

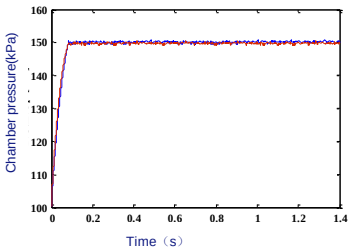


2kPa 1kPa 0.5kPa 0kPa

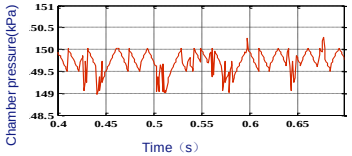
3 Pneumatic microvalve and system

PWM controller: modulations duty cycles

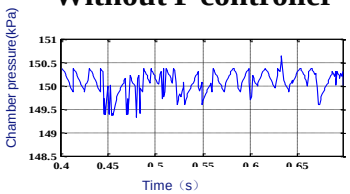
$$u(t)=\begin{cases}1 & (j-1)T\le t<(j-1+D)T\\ 0 & (j-1+D)T\le t<jT\end{cases}\qquad j=1,2,\ldots,n$$



Pressure control performance impact of the pneumatic micro actuator with P controller or without P controller

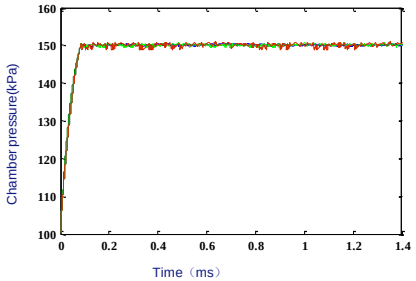


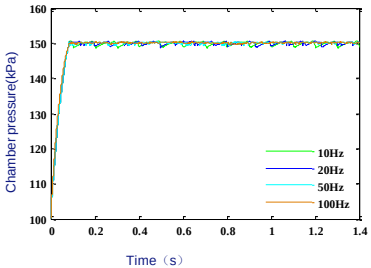
Without P controller



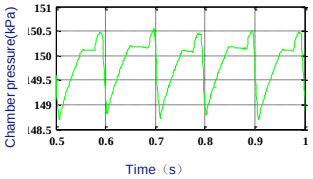
With P controller

Pressure control performance impact of the micro actuator with different PWM carrier amplitudes

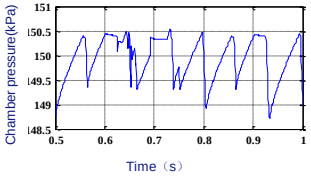




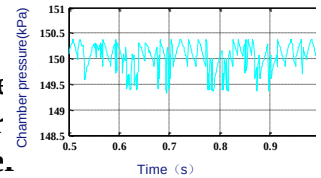
Pressure control performance impact of the pneumatic micro actuator with different PWM carrier frequencies



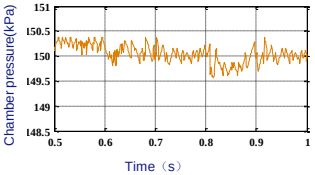
10Hz



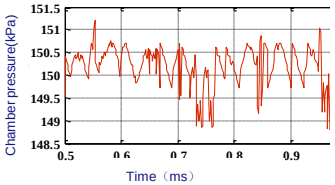
20Hz



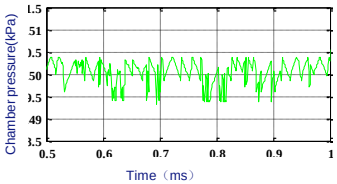
50Hz



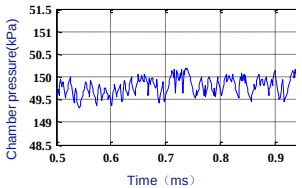
100Hz



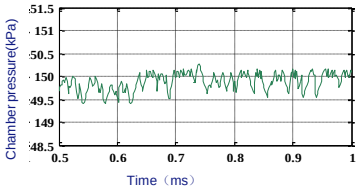
2kPa



1kPa



0.5kPa



0.1kPa

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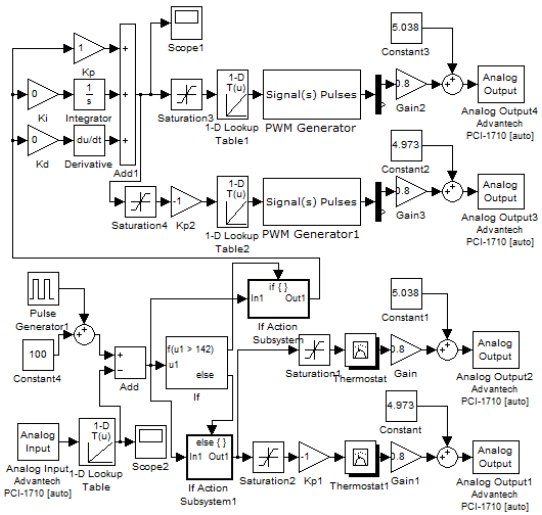
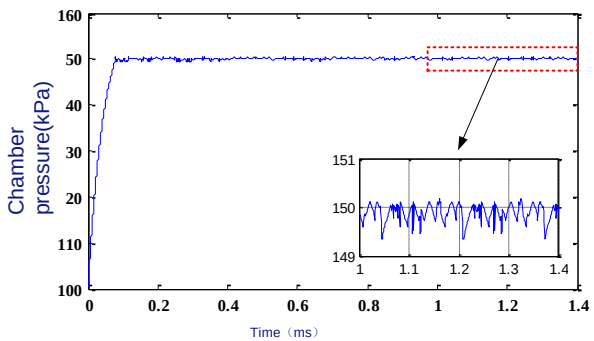
3 Pneumatic microvalve and system

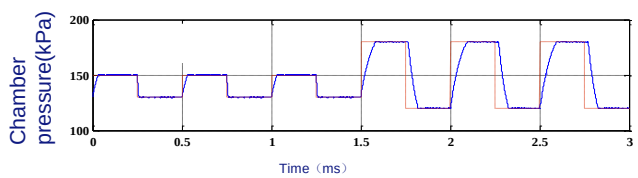
Composite controller: **Bang-Bang+P+PWM composite controller**

Composite controller model of the actuated chamber pressure

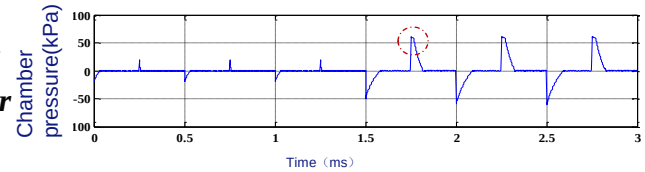




Step response curve of *the actuated chamber* pressure using composite control method (150kPa)



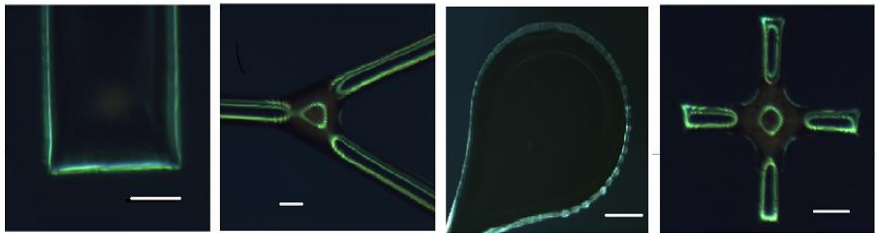
Actuated chamber pressure change process of the actuator chamber tracking step signal



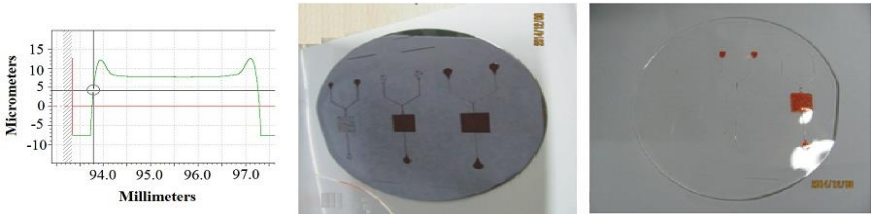
Tracking error change process

3 Pneumatic microvalve and system

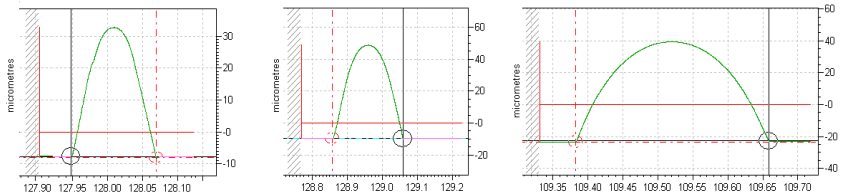
Microscope pictures of arc molds



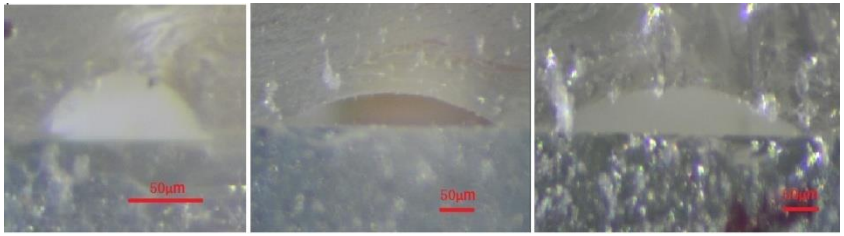
Pictures of damaged mold and patterned PDMS block



Pictures of arc molds surface profiles



Microscope pictures of PDMS cast surfaces



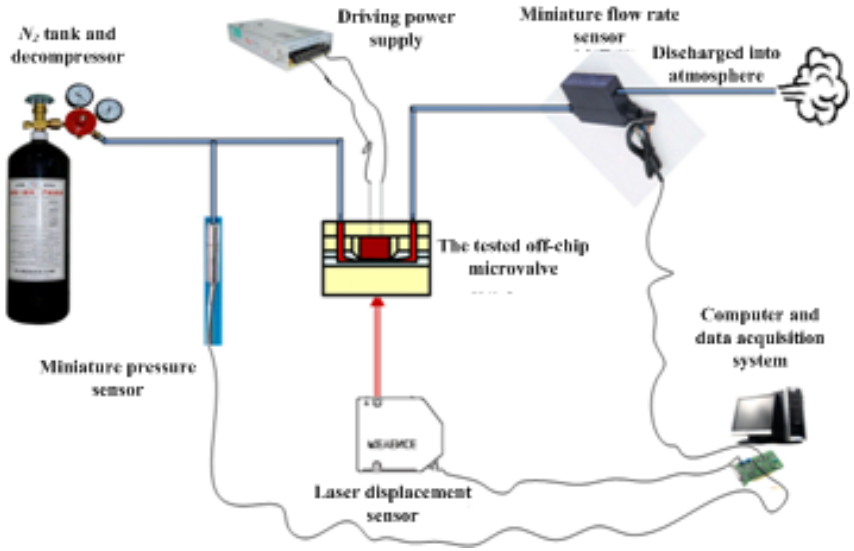
128μm
40μm

202μm
58μm

276μm
62.6μm

3 Pneumatic microvalve and system

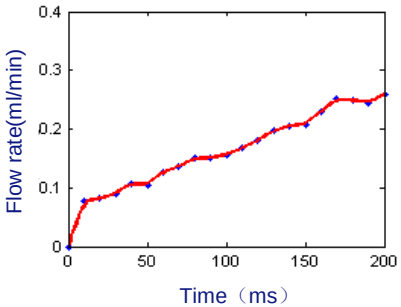
Experimental research



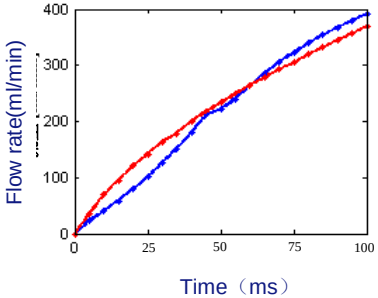
Schematic diagram of performance measurement for the off-chip microvalve

Comparison between the spool actuated force results

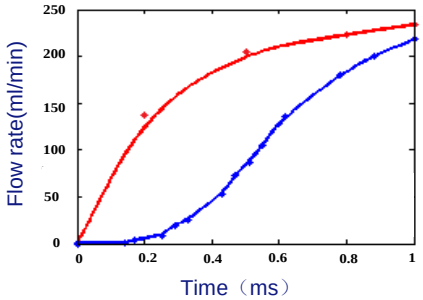
NO	Parameters	Valves
1	Experiment /N	0. 844
2	Simulation / N	0. 88 1
2	Theory /N	0. 983
3	Design demand /N	0. 220



Leak rate

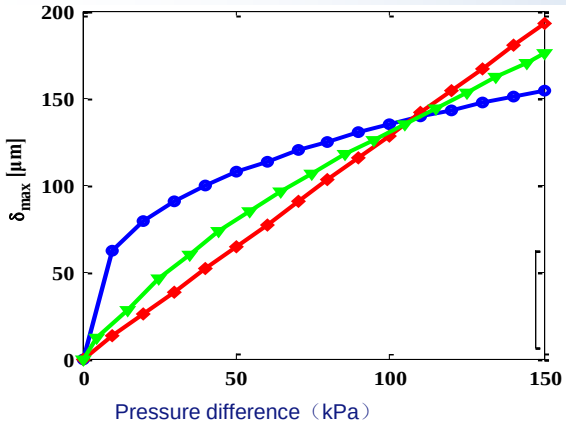


Flow rate under fully open

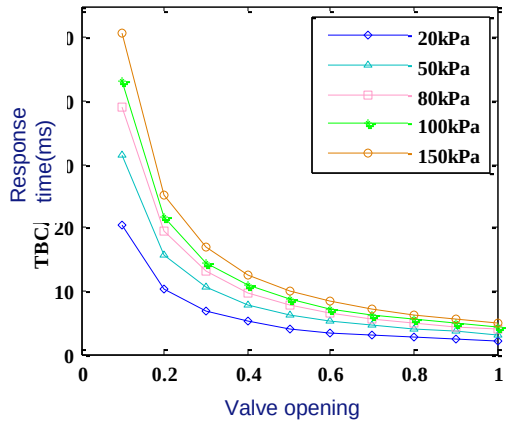


Measurement results when differential pressure is 50kPa

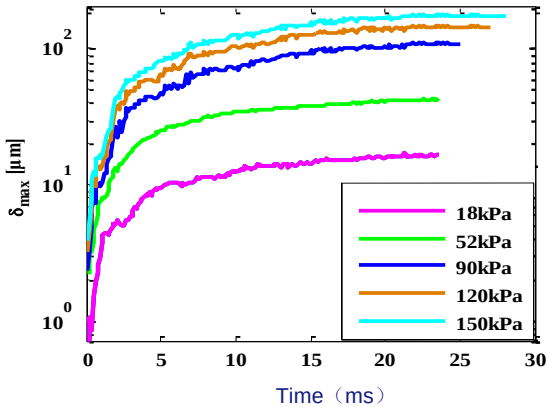
3 Pneumatic microvalve and system



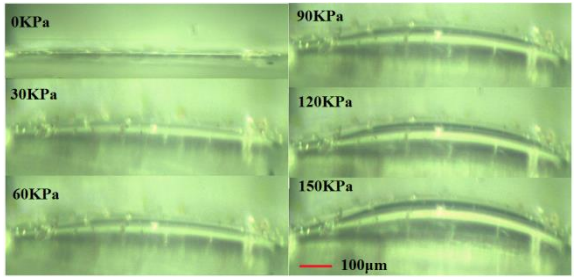
Experimental results compared with the theoretical calculation and FEM results of the PDMS actuated membrane maximum deflection versus different pressures with dimension 500μm×200μm×40μm



Response time simulation results of the pneumatic micro actuator with different valve-openings of the electromagnetic microvalve 1



Dynamic response testing curves of the pneumatic micro actuator maximum deflection with the actuated part dimension 200μm×500μm



Microscope images of the PDMS actuated membrane deformations versus different pressures with the actuated part dimension 200μm×500μm

Comparison between experimental results and theoretical calculation results about response time of the pneumatic micro actuator (valve-opening of the electromagnetic microvalve 1 is 20%)

充气压力（kPa）	16	52	90	120	150
Theoretical inflation time t_{I} (ms)	0	0	0	1.26	2.23
Theoretical inflation time t_{II} (ms)	9.69	16.01	20.65	21.86	23.05
Theoretical total inflation time t(ms)	9.69	16.01	20.65	23.12	25.28
Experimental total inflation time t_s(ms)	10.05	15.2	19.72	24.93	27.19
Error δ%	-3.72%	5.06%	4.52%	-7.85%	-7.55%

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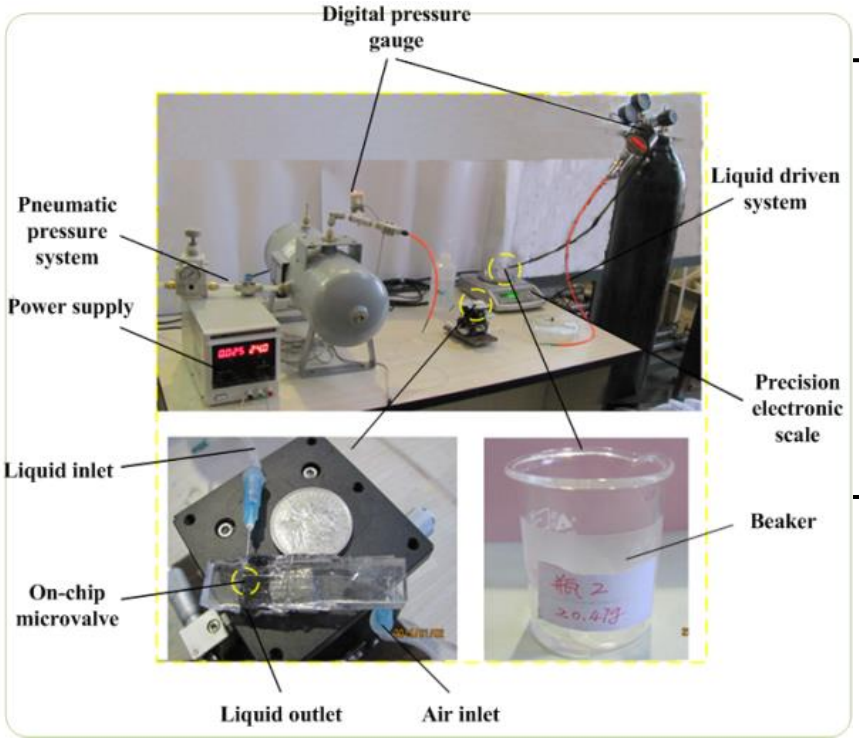
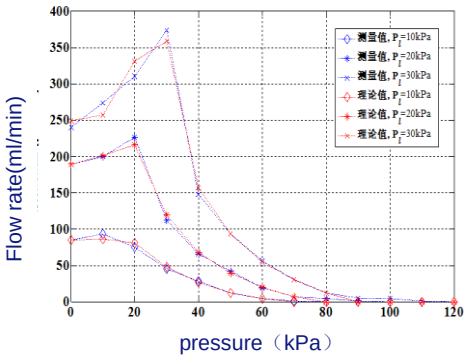
3 Pneumatic microvalve and system



Test bench for liquid flow rate of the membrane microvalve

Liquid flow rates measuring results with different valve-openings of the membrane microvalve (μL/min)

Pneumatic pressure kPa \ Driven liquid kPa	10	20	30
0	85	189	240
10	93	200	274
20	75	226	310
30	45	112	374
40	28	66	148
50	12	42	93
60	4	19	56
70	1	7	30
80	0	4	12
90	0	1	5
100	0	0	4
110	0	0	1
120	0	0	0



Comparison between modified theoretical results and experimental datas about liquid flow rate of the membrane microvalve

3 Pneumatic microvalve and system

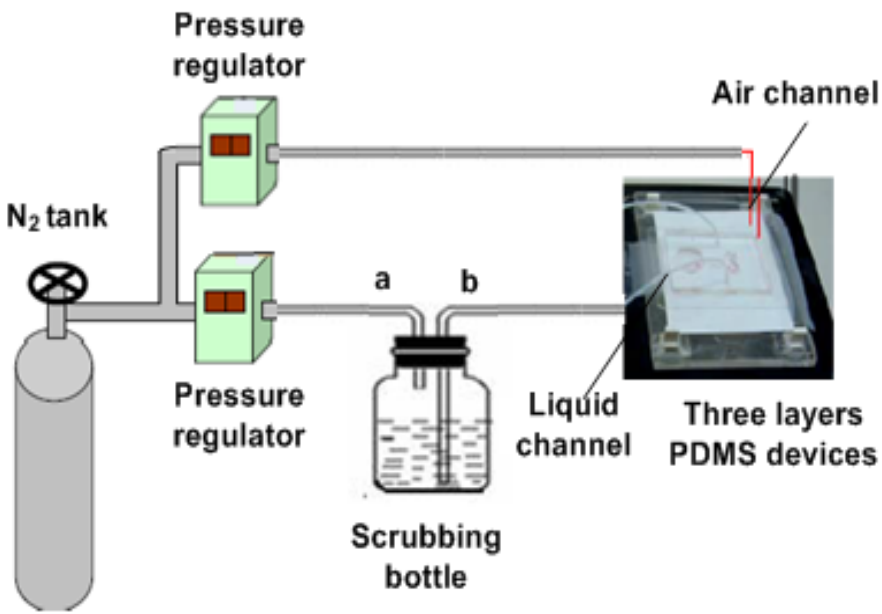
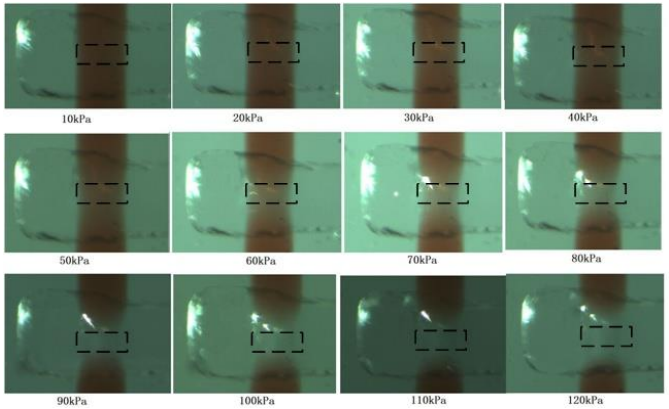
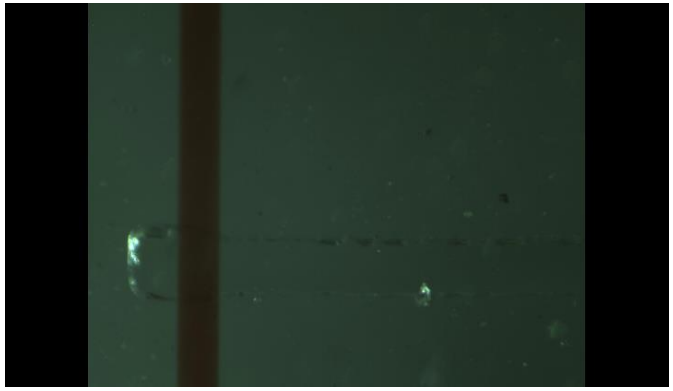


Diagram of fluid driving setup





Compressed-air driven liquid system， a compressed-air driven liquid system is used for controlling the accurate differential pressure for the liquid microchannels, The compressed air system linked to the air channels is used for control the air pressure in the pneumatic actuators.

3 Pneumatic microvalve and system

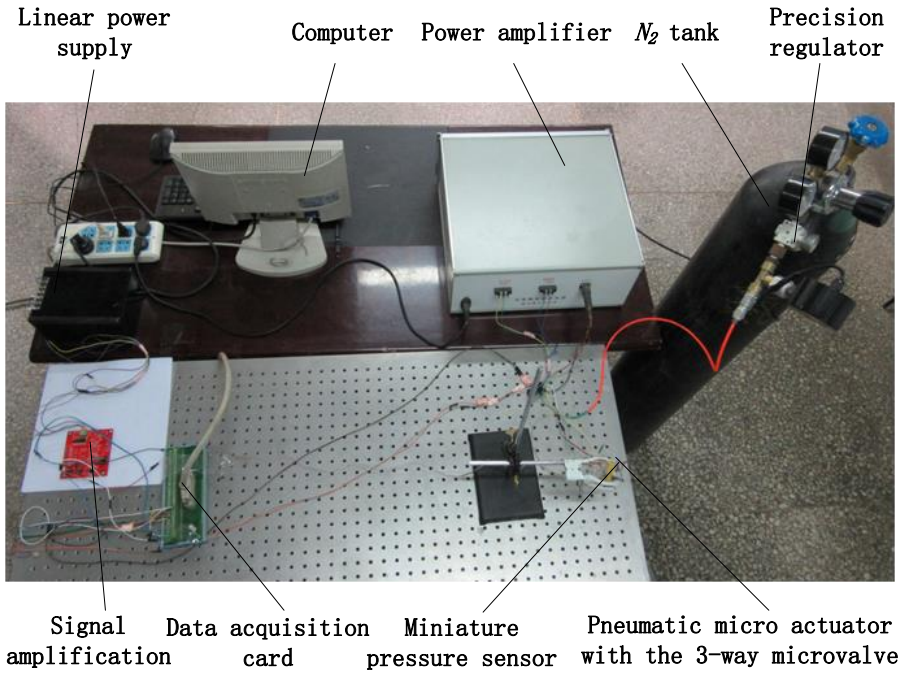
Main performances

1.Less than accuracy 1kPa；
2.Working pressure 100kPa；
3.Responding speed（1ms<rt<1s）；

Miniature pressure sensor XCQ-062

PCI-1710-CE data acquisition card

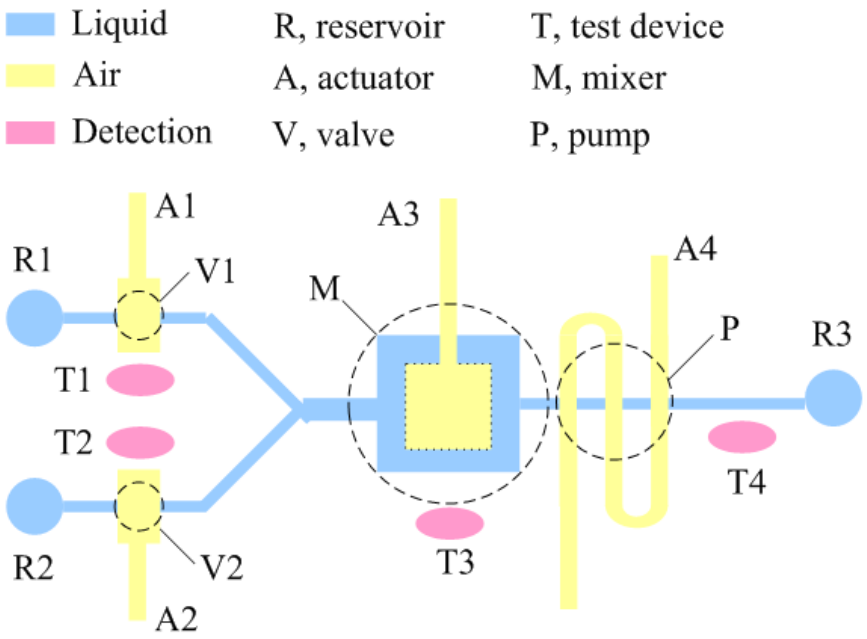
Signal amplification



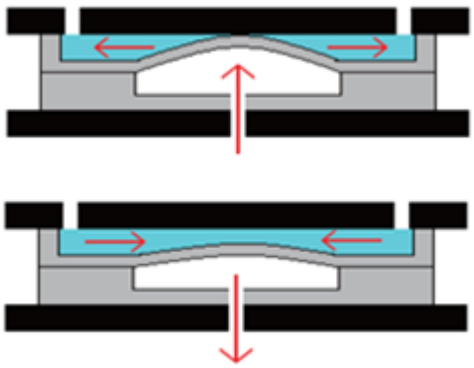
Experimental setup of PDMS pneumatic micro actuator of the on-chip microvalve

4 Applications

pneumatic micro mixing chip



Structure of the pneumatic micro mixing chip

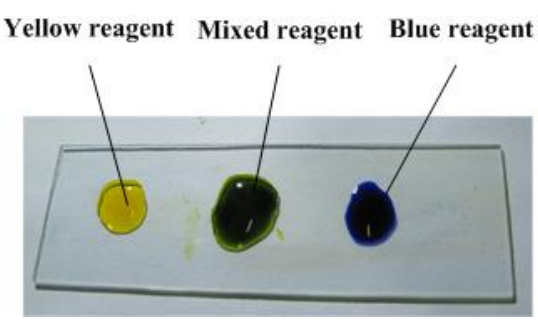


PDMS actuated membrane motion in a cycle

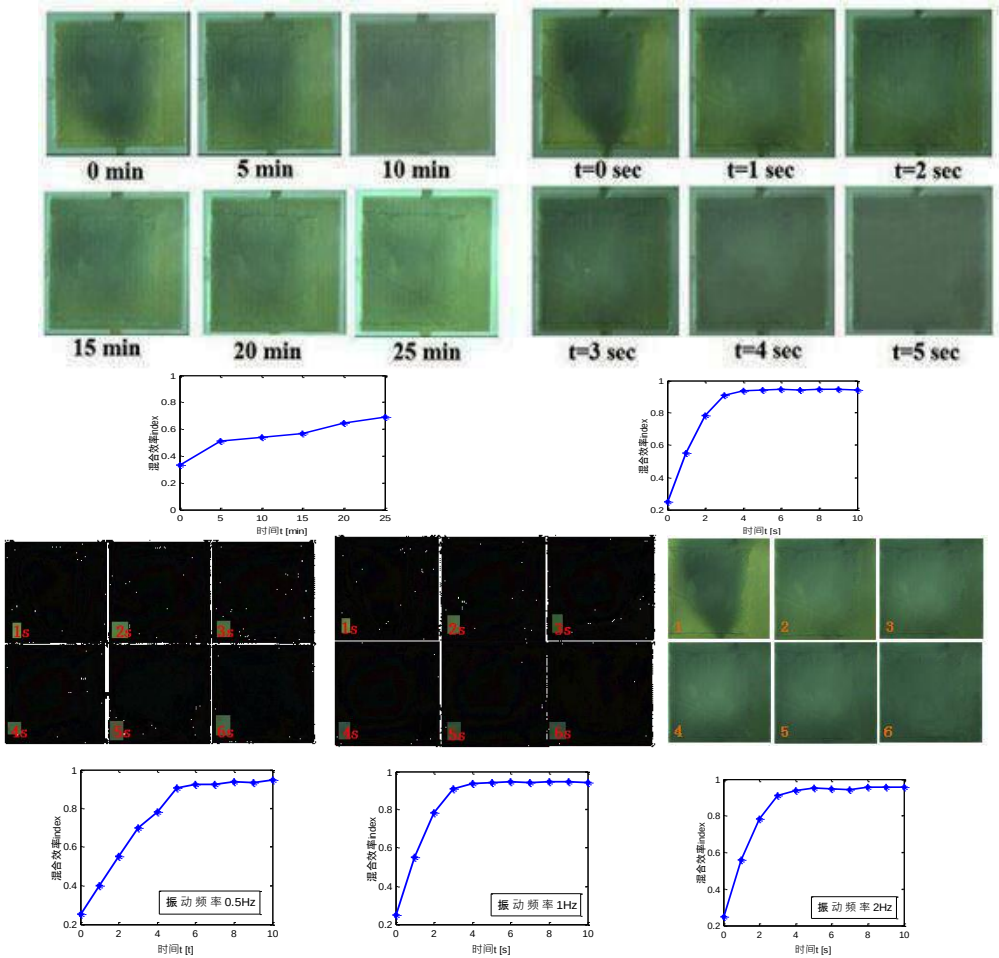
Reagents motion of the micro mixing chamber in a cycle

4 Applications

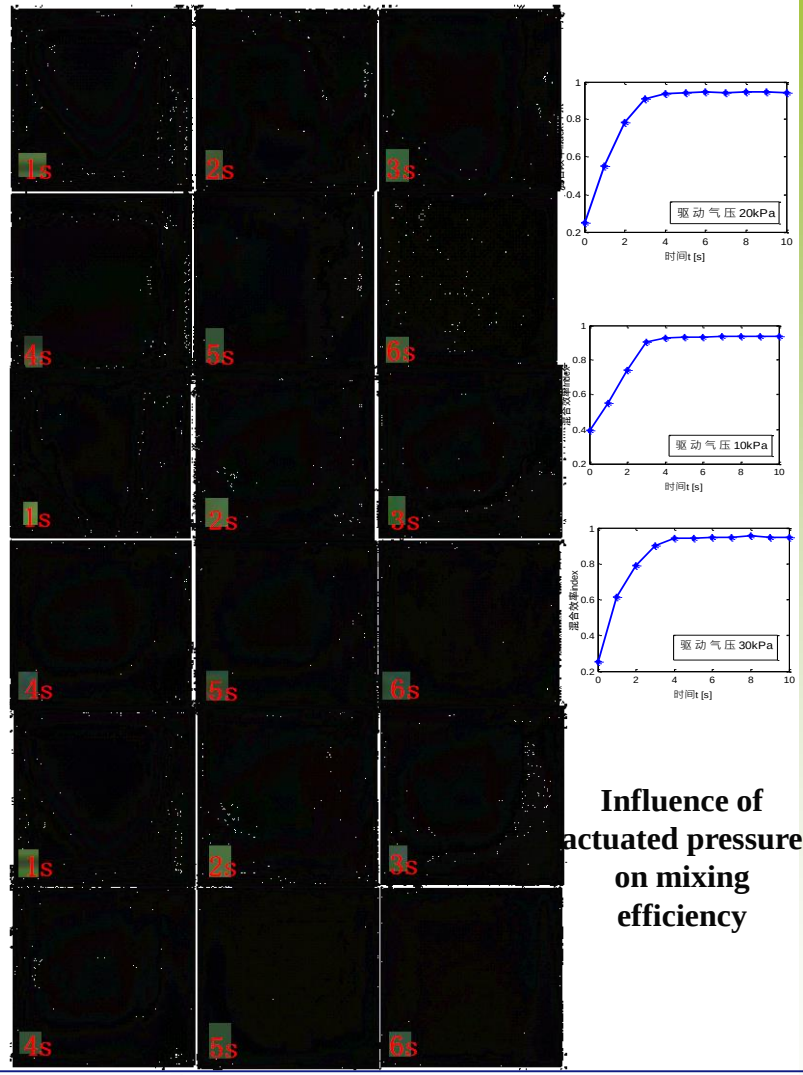
Test bench for measuring the micro mixing chip performances



4 Applications



Influence of vibrating frequency on mixing efficiency



Influence of actuated pressure on mixing efficiency

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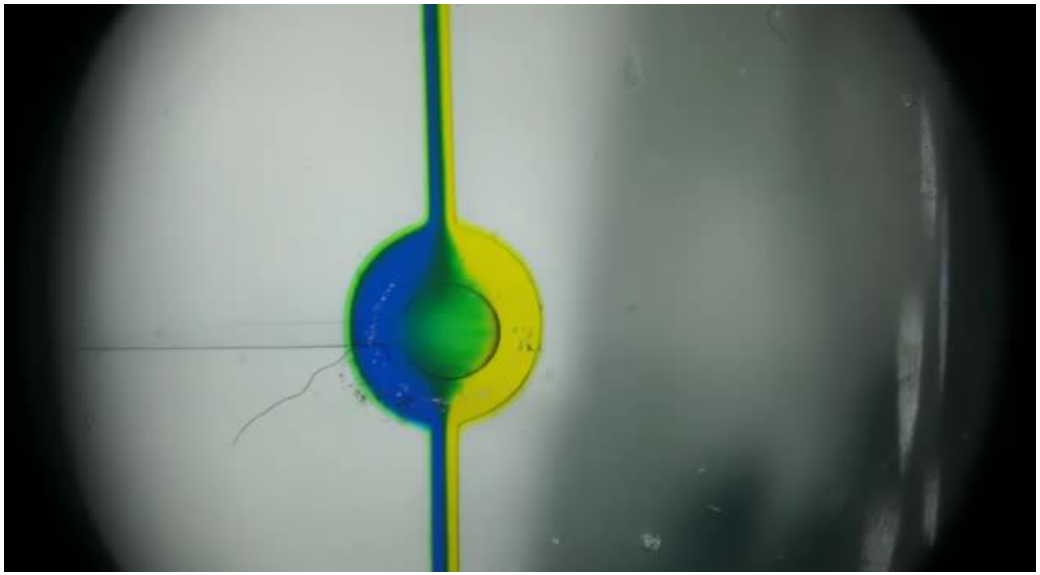

5 Conclusions and outlooks

Conclusions

- pneumatic microvalves can be easily integrated with microchips and fabricated if the valve body was made of PDMS.
- pneumatic microfluidic systems can be controlled by the PDMS microvalves to realize the pressure control below 200kPa.
- PDMS pneumatic microvalves can be applied in micro-mixer chips to improve the mixing effieciency.

Future work

- Improve the accuracy of the pressure control and responding speed.
- Make further integration of the valve group for large scale integration.
- To develop wireless and remote control model for microfluidic systems.

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Thank you for your attention!

lisongjing@hit.edu.cn