Sensors and Actuators A 233 (2015) 548–556

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Self-priming bubble tolerant microcylinder pump

Tine Dolžan, Borut Pečar*, Matej Možek, Drago Resnik, Danilo Vrtačnik

University of Ljubljana, Faculty of Electrical Engineering, Laboratory of Microsensor Structures and Electronics, Tržaška 25, SI-1000 Ljubljana, Slovenia

ARTICLE INFO

Article history:
Received 26 January 2015
Received in revised form 15 July 2015
Accepted 15 July 2015
Available online 26 July 2015

Keywords:
Micropump
Numerical simulation
Polydimethylsiloxane (PDMS)
Bubble tolerance
3D Fully coupled model

ABSTRACT

Development, numerical optimization, and fabrication of piezoelectric microcylinder pumps are presented. Innovative design is based on a centrally placed inlet port which leads directly into the center of the pumping chamber. Unique features of microcylinder pumps were developed through virtual device prototyping, using an advanced 3D fully coupled electro-mechanical-fluidic (EMF) model built in COMSOL Multiphysics 4.3b simulation environment. To validate developed simulation model, microcylinder pumps with various pumping chamber diameters were fabricated employing soft lithography process. Pumping chamber optimal diameter was further confirmed with measurements on fabricated prototypes. For maximum performance evaluation, optimized microcylinder pump was characterized in detail with square wave excitation signal. Optimized micropump prototype exhibits flow rates up to 2.3 ml min^{-1}/8 ml min^{-1}, backpressures up to 520 mbar/55 mbar, and suction pressures down to −480 mbar/−85 mbar for DI water and air, respectively. Furthermore, it features self-priming ability and high level of bubble tolerance.

1. Introduction

Micropumps represent an essential component of microfluidic systems where precisely controlled transport of fluids is crucial e.g., in μTAS systems, drug delivery systems, and others. A number of micropumps have been previously reported employing various working mechanisms and actuation principles, exhibiting high variability in performance and reliability [1]. According to the operating principle, micropumps can be classified either as displacement or dynamic [2]. Vast majority of reciprocating displacement category represent diaphragm micropumps, which can be further classified according to actuation principle (piezoelectric, electromagnetic, electrostatic, and others), valve types (flap valve, fixed-geometry, throttle), number of chambers, pumping direction, or other criteria [3,4].

For development and optimization of novel micropump prototypes, a detailed understanding of operation principles and microfluidic phenomena is essential. For this purpose, several 3D fully coupled electro-mechanical-fluidic (EMF) models based on finite element method (FEM) have been employed, concentrating primarily on diffuser type micropumps [5,6]. Some of proposed models have also been experimentally verified [7,8]. Reported simplified 2D models require less computational power and time but yield inaccurate results [9,10]. Structurally stationary simulation of microthrottle pump with no fluid within the structure was reported by Johnston et al. [11].

Micropump performance is defined by flow rate and backpressure characteristics. Moreover, for real-life micropump applications, reliability is crucial. Micropump reliability can be significantly improved with appropriate design [12,13]. In real-life microfluidic systems, it is almost impossible to completely eliminate the presence of gas bubbles in fluid as they may be introduced into the pumping chamber directly from the inlet or formed due to cavitation or degassing phenomena [14,15]. In such case, micropump should be able to expel bubbles from pumping chamber and continue with operation. Level of bubble tolerance is defined with micropump ability to expel bubbles up to a certain volume [16]. If self-priming is required, micropumps have to be capable of pumping gases and exhibit negative pressure (suction pressure) at the inlet [17].

Volumetric flow rate change in a flat (channel height significantly smaller than channel width) rectangular channel at constant pressure difference is cubic proportional to the channel height, and linearly proportional to channel width [18,19]. First reported microthrottle pumps are based on this principle, employing deformable channel in an elastomer substrate and three PZT actuators to implement the variable flow resistances [20]. Later reported microthrottle pumps employ a single piezoelectric actuator shifted in respect to pumping chamber. Throttles are placed near the points of membrane deflection extrema [11]. Strip-type

* Corresponding author.
E-mail addresses: tine.dolzan@fe.uni-lj.si (T. Dolžan), borut.pecar@fe.uni-lj.si (B. Pečar), matej.mozek@fe.uni-lj.si (M. Možek), drago.resnik@fe.uni-lj.si (D. Resnik), danilo.vrtacnik@fe.uni-lj.si (D. Vrtačnik).

http://dx.doi.org/10.1016/j.sna.2015.07.015
0924-4247/

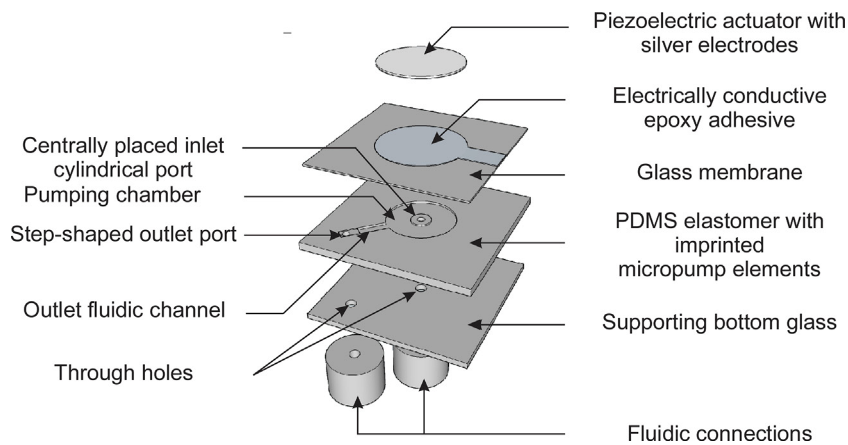

Fig. 1. MCP exploded view (dimensions are not to scale).

microthrottle pump is a variation where pumping chamber and piezoelectric actuator are both strip-shaped, which enable a more efficient surface utilization compared to micropumps comprising disk-shaped actuators [21].

Here, we present development, optimization, and fabrication of a novel microcylinder pump (MCP). This type of micropump is based on a centrally placed inlet cylindrical port led directly into the center of the pumping chamber and on actuated glass membrane that is loosely attached via a resilient elastomer to the bottom of the supporting glass. Central alignment of pumping chamber, piezoelectric (PZT) actuator and inlet rectifying element allow the pumping chamber to be larger than in conventional microthrottle pump design, thus, enabling operation at lower excitation frequencies and consequentially inhibiting occurrence of cavitation. This approach increases the compression ratio at predefined chamber depth which leads to micropump self-priming ability and high level of bubble tolerance. Proposed MCP prototypes were designed with respect to additional favorable properties e.g., high flow rate, backpressure, and suction pressure performance. Above listed properties assure MCP usability in number of microfluidic applications where high reliability is required. MCP structure comprises biocompatible materials (glass and PDMS), which further extends micropump versatility to biomedical applications [22]. Proposed MCP design should excel particularly in the case of pumping biological cells, which should not be squeezed during manipulation. This can be achieved by partial closing of inlet cylindrical port and outlet fluidic port. Furthermore, the MCP design should enable the valve mode of operation where centrally placed cylindrical inlet port acts as a normally open DC controlled valve, which completely seals fluidic path. If two proposed MCP designs are counter facing, bidirectional pumping can be achieved.

2. Microcylinder pump design

Virtual prototyping and performance evaluation of previously reported microthrottle pump [11,20,23,24] using a 3D fully coupled electromechanical fluidic model built in COMSOL Multiphysics 4.3b [21] has shown an increase of flow rate and backpressure performance at a predefined frequency by increasing the surface area of pumping chamber [25]. Our further simulation results have shown that comparable flow rate and backpressure performance is achieved by implementing a smaller pumping chamber, but at higher excitation frequency. Such increased excitation frequency results in an increased risk of cavitation. If the compression ratio (ratio between stroke and dead volume) is maintained, a reduction of surface area also dictates shallower pumping chamber. However, the latter is increasing the risk of clogging. On the other hand,

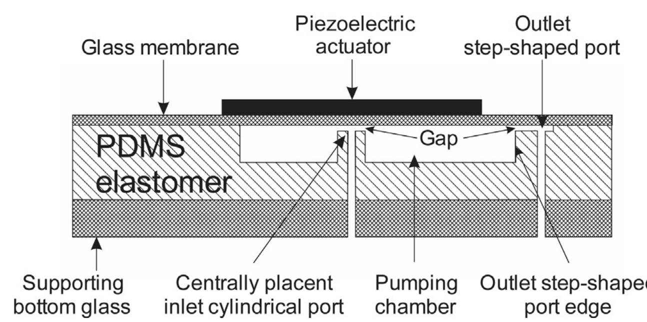

Fig. 2. MCP cross-section view (dimensions are not to scale).

a deeper pumping chamber would decrease the compression ratio, which would impede pump self-priming ability and bubble tolerance [12].

In order to assure maximum inlet rectifying efficiency, the inlet rectifying element (can be either cylinder, throttle...) should be centrally aligned with the area where vertical membrane deformation is the largest [25]. This area is located directly underneath the PZT actuator, therefore, the PZT actuator and pumping chamber should be centrally aligned. Central alignment of pumping chamber, piezoelectric (PZT) actuator, and inlet rectifying element results in highest flow rate and backpressure performance.

Above listed design considerations led to the proposed novel MicroCylinder Pump (MCP) design, which features a vertical fluid inlet port leading directly into the center of the pumping chamber. The latter enables implementation of large pumping chamber and ensures maximum efficiency of inlet rectifying element.

Figs. 1 and 2 are showing the proposed MCP design. Fluidic connections are located on the outside side of supporting bottom glass, which is covered with a resilient elastomer. Elastomer layer contains the following microfluidic elements: pumping chamber, centrally placed inlet cylindrical fluidic port, outlet fluidic channel, and step shaped outlet port. Piezoelectric actuator is attached on the top glass membrane, which seals the pumping chamber and outlet fluidic channel.

3. Microcylinder pump operation

Microcylinder pump operation is depicted in Fig. 3, showing the two distinctive operation cycle phases. In order to achieve counter phase action of inlet and outlet fluidic port during membrane expansion and compression, the outlet fluidic port has to be positioned outside of the pumping chamber. The distance between