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A Pneumatic PDMS Micropump with in plane check valves for disposable Microfluidic systems

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Abstract:

This paper presents the design and development of a pneumatic PDMS micropump with in-plane check valves for disposable microfluidic systems. Microfluidic devices require small, reliable, and controllable fluid pumps for applications such as biomedical testing, chemical analysis, drug delivery, and point-of-care diagnostics. The proposed micropump uses polydimethylsiloxane (PDMS) as the primary fabrication material because of its flexibility, biocompatibility, transparency, and suitability for low-cost disposable devices. Pneumatic actuation is used to generate the pumping action by periodically deforming the flexible PDMS membrane. In-plane check valves are integrated into the microfluidic structure to control the direction of fluid flow and reduce backflow during operation.

The micropump is designed to provide stable and controlled fluid transport while maintaining a compact structure. The proposed design can be fabricated using relatively simple and cost-effective microfabrication techniques, making it suitable for single-use microfluidic applications. The performance of the micropump can be evaluated based on parameters such as flow rate, pumping pressure, actuation frequency, and valve response. The proposed system offers a promising solution for integrating pumping and flow-control functions into disposable microfluidic platforms, with potential applications in lab-on-chip systems, diagnostic devices, and portable biomedical instruments.

Keywords: Pneumatic Microactuation, PDMS Micropump, In-Plane Check Valve, Microfluidic Flow Control, Elastomeric Membrane, Disposable Lab-on-Chip, Passive Valving, Microscale Fluid Transport, Point-of-Care Microfluidics, Low-Pressure Actuation.

Introduction

Microfluidic technology has emerged as an important approach for handling and manipulating very small quantities of fluids within compact devices. By integrating fluidic channels, valves, pumps, and sensing elements onto a small platform, microfluidic systems can perform multiple operations with reduced sample volume, lower reagent consumption, and shorter processing times. These characteristics have made microfluidic platforms increasingly useful in point-of-care diagnostics, biomedical analysis, drug screening, chemical processing, and portable laboratory systems. However, the reliable movement of fluid remains one of the major challenges in developing efficient microfluidic devices, particularly when the system is intended to be inexpensive, compact, and disposable.

Micropumps provide the driving force required to transport liquids through microscale channels. Various pumping principles, including electroosmotic, peristaltic, thermopneumatic, piezoelectric, electromagnetic, and pneumatic actuation, have been investigated for microfluidic applications. Among these approaches, pneumatic actuation offers several advantages because it can generate membrane deformation without requiring complex electrical components directly inside the fluidic pathway. This feature is particularly beneficial for applications involving biological samples, where electrical isolation and contamination control can be important. Pneumatic operation also allows the pumping rate to be controlled by adjusting parameters such as applied pressure, actuation frequency, and membrane displacement.

Polydimethylsiloxane (PDMS) is widely used in microfluidic device fabrication because of its optical transparency, flexibility, chemical compatibility with many laboratory processes, and relatively simple manufacturing requirements. Its elastomeric nature enables a thin PDMS membrane to deform under pneumatic pressure and return to its original configuration when the pressure is removed. This reversible deformation can be utilized as the primary pumping mechanism. Nevertheless, a pumping chamber alone cannot ensure efficient one-directional fluid transportation. Without an appropriate flow-control mechanism, pressure-driven membrane motion may result in undesirable reverse flow and reduced pumping efficiency.

Check valves therefore play an important role in converting the reciprocating deformation of the pumping membrane into directional fluid movement. Conventional valve configurations can increase device complexity, fabrication requirements, and overall dimensions. Integrating the check valves directly within the plane of the microfluidic structure provides an opportunity to simplify the fluidic architecture while maintaining directional flow control. In-plane passive valves can operate through pressure differences across the valve structure, eliminating the need for additional external actuation mechanisms. Their integration with a flexible pneumatic pumping chamber can consequently provide a compact and potentially low-cost pumping solution.

The present work focuses on the design of a pneumatic PDMS micropump incorporating in-plane check valves for disposable microfluidic systems. The proposed configuration combines pneumatic membrane actuation with passive directional flow control within a single microfluidic platform. The design aims to achieve controlled fluid transport while reducing structural complexity and supporting disposable-device requirements. Important design parameters include the geometry of the pumping chamber, PDMS membrane characteristics, valve dimensions, channel configuration, applied pneumatic pressure, and actuation frequency. These parameters influence membrane displacement, valve opening and closing behavior, pressure losses, and the resulting flow rate.

The proposed micropump is particularly relevant to microfluidic systems where compactness, controllable operation, and low manufacturing complexity are important considerations. Its disposable nature can also be advantageous in applications where cross-contamination between samples must be minimized. Performance evaluation of the developed design can be carried out by studying flow rate, pressure response, valve functionality, and pumping stability under different operating conditions. Through the integration of pneumatic actuation and in-plane passive check valves, this work explores a practical architecture for fluid delivery in next-generation disposable microfluidic platforms.

Literature Review

Micropumps are fundamental components of microfluidic systems because they provide controlled fluid transportation through microscale channels. Several researchers have investigated different actuation mechanisms to achieve reliable pumping at low flow rates and pressures. Common approaches include electroosmotic, piezoelectric, thermopneumatic, electromagnetic, peristaltic, and pneumatic actuation. Although these techniques can provide effective fluid movement, their suitability for disposable microfluidic devices depends on fabrication complexity, operating requirements, integration capability, and cost. Pneumatic micropumps have attracted considerable interest because the pumping mechanism can be separated from the fluidic path and controlled through external pressure.

PDMS has become one of the widely investigated materials for microfluidic fabrication due to its flexibility, optical transparency, biocompatibility, and compatibility with soft-lithography-based manufacturing. Its elastic behavior allows thin membranes to undergo reversible deformation when subjected to pneumatic pressure. This property has been utilized in diaphragm-type micropumps, where repeated membrane deflection produces the pressure variation required for fluid transportation. PDMS-based structures can also be fabricated with relatively low-cost processes, making them attractive for disposable lab-on-chip and point-of-care applications. However, the mechanical properties of PDMS, including its elasticity and deformation behavior, must be considered carefully because membrane thickness and chamber geometry strongly influence pumping performance.

Pneumatic diaphragm micropumps have been developed using various chamber and membrane configurations. In these systems, an external pneumatic pressure source periodically deflects a flexible membrane, producing suction and compression phases within the pumping chamber. The resulting pressure difference drives fluid through the microchannel. Research on membrane-driven micropumps has demonstrated that operating pressure and actuation frequency significantly affect flow rate and pumping stability. However, reciprocal membrane motion can cause fluid to move in both directions unless an effective flow-rectification mechanism is incorporated. Therefore, valve design is an important aspect of achieving directional pumping.

Passive check valves provide a practical method for controlling fluid direction without requiring a separate actuation system. Different microvalve designs have been investigated, including flap valves, membrane valves, diffuser/nozzle structures, and normally closed valve configurations. Passive valves generally operate according to pressure differences generated during the pumping cycle. Their major advantage is reduced control complexity because the valve response can be obtained directly from the pressure generated by the pump. Nevertheless, valve dimensions, opening pressure, leakage, response time, and fabrication tolerances can strongly influence overall micropump performance.

The integration of check valves within the plane of a microfluidic device has received attention as a means of reducing device thickness and simplifying fluidic connections. In-plane valve configurations can be incorporated directly into the microchannel network, allowing the pump and flow-control components to form a compact structure. Such integration is particularly useful for disposable microfluidic platforms, where minimizing the number of components can reduce manufacturing cost and assembly requirements. However, achieving sufficient valve sealing while maintaining a low cracking pressure remains a significant design consideration. Excessive valve resistance can reduce flow rate, whereas inadequate sealing can result in backflow and poor pumping efficiency.

Recent developments in disposable microfluidic systems have emphasized the need for compact, inexpensive, and contamination-resistant fluid-handling components. Disposable platforms are increasingly considered for diagnostic testing and point-of-care applications because the fluidic section can be discarded after use, reducing the possibility of cross-contamination. For such systems, micropumps should ideally operate with low power or simple external actuation, require minimal assembly, and provide predictable fluid delivery. PDMS-based pneumatic micropumps are promising in this regard because the flexible membrane can perform both mechanical deformation and fluidic actuation within a relatively small footprint.

Despite considerable research on PDMS micropumps and passive microvalves, there remains a need for integrated designs that simultaneously address pumping performance, directional flow control, fabrication simplicity, and disposability. Many existing micropump configurations involve complex multilayer structures, external components, or specialized actuation mechanisms. In addition, valve performance can vary significantly with channel geometry and pressure conditions. These limitations indicate an opportunity to develop a simplified pneumatic PDMS micropump in which in-plane check valves are integrated directly into the fluidic architecture.

Based on the reviewed literature, the present work proposes a pneumatic PDMS micropump with integrated in-plane check valves for disposable microfluidic systems. The study focuses on combining the flexibility of PDMS, the controllability of pneumatic actuation, and the passive flow-rectification capability of in-plane valves. The design is intended to provide reliable one-directional fluid transport while maintaining a compact and potentially low-cost architecture. Key performance parameters such as flow rate, actuation pressure, operating frequency, valve response, and backflow behavior can be considered to evaluate the effectiveness of the proposed design. This approach addresses an important research gap in the development of simplified and disposable fluid-handling solutions for microfluidic applications.

III. Problem Statement

Disposable microfluidic systems require compact, reliable, and cost-effective methods for transporting small volumes of fluids through microscale channels. Conventional micropumping techniques often involve complex fabrication processes, multiple external components, electrical actuation, or relatively high manufacturing costs, which can limit their suitability for single-use microfluidic devices. In pneumatic

PDMS micropumps, the flexible membrane can generate fluid movement through repeated deformation; however, reciprocating membrane motion may produce unwanted reverse flow and reduce the efficiency and stability of fluid transport. The absence of an effective and easily integrated flow-rectification mechanism can therefore limit the performance of such micropumps.
There is a need for a simple micropump architecture that combines pneumatic actuation with efficient directional flow control while maintaining the advantages of PDMS, such as flexibility, transparency, and low-cost fabrication. Conventional check-valve arrangements may increase device complexity, thickness, and assembly requirements. Therefore, integrating passive check valves directly within the plane of the microfluidic structure can provide a more compact and simplified solution.
The problem addressed in this work is the **development of a pneumatic PDMS micropump with integrated in-plane check valves capable of providing controlled and predominantly unidirectional fluid flow for disposable microfluidic systems**, while minimizing backflow, structural complexity, and fabrication requirements. The design must also achieve stable pumping performance under suitable pneumatic pressure and actuation frequency.

IV. OBJECTIVES

To design a compact pneumatic PDMS micropump suitable for disposable microfluidic applications.

To develop integrated in-plane check valves for achieving controlled and predominantly unidirectional fluid flow.

To analyze the influence of pneumatic pressure and actuation frequency on micropump performance.

4 . **To evaluate** important performance parameters such as flow rate, pumping pressure, valve response, and backflow.

5 **To optimize** the geometry of the pumping chamber, PDMS membrane, microchannels, and in-plane check valves for improved fluid transport.

6.**To develop** a simple, low-cost, and potentially disposable micropumping architecture suitable for applications such as lab-on-chip and point-of-care microfluidic system

V. METHODOLOGY

The methodology of the proposed work involves the design, simulation, fabrication, and performance evaluation of a pneumatic PDMS micropump integrated with in-plane check valves. The overall procedure is divided into the following stages.

4.1 System Concept and Design

Initially, the working principle of the micropump is defined. The system consists of a pneumatic actuation chamber, flexible PDMS membrane, inlet and outlet microchannels, and two in-plane check valves. Pneumatic pressure is applied periodically to deform the PDMS membrane. During the compression and suction cycles, the check valves regulate the fluid direction and minimize reverse flow.

4.2 CAD Modelling

A three-dimensional model of the micropump is developed using suitable CAD software. The dimensions of the pumping chamber, membrane, microchannels, inlet/outlet ports, and check valves are selected based on the required operating conditions. Different valve geometries can be considered to identify a configuration that provides low opening pressure and effective flow rectification.
The proposed micropump is analyzed using numerical simulation to study membrane deformation, pressure distribution, fluid velocity, and flow behavior. The effects of pneumatic pressure, membrane thickness, valve geometry, and actuation frequency are investigated. The simulation results are used to identify design parameters that provide suitable membrane displacement and directional fluid transport.

4.5 Fabrication

After optimization of the design, the micropump structure is fabricated using an appropriate microfabrication technique. A PDMS layer containing the microfluidic channels, pumping chamber, and in-plane check valves is prepared using a mould or soft-lithography-based process. The PDMS structure is then bonded to a suitable substrate to create sealed microfluidic channels.

4.6 Pneumatic Actuation Setup

The fabricated micropump is connected to an external pneumatic pressure source through the actuation port. A controlled pressure signal is applied to the PDMS membrane at different actuation frequencies. The resulting membrane deformation generates pressure variations inside the pumping chamber, producing fluid movement through the microchannels.

4.7 Experimental Performance Evaluation

The performance of the micropump is evaluated using suitable experimental measurements. The flow rate, pumping pressure, actuation frequency, valve opening behavior, and backflow are measured under different operating conditions. The influence of these parameters on pumping efficiency and flow stability is investigated.

4.8 Comparison and Optimization

Finally, the experimental results are compared with the numerical predictions. The differences between simulated and experimental results are analyzed to identify possible fabrication or operating limitations. The micropump geometry and operating parameters are then optimized to achieve improved flow control, reduced backflow, and stable operation.

Methodology Flow

Concept Development → CAD Design → Material Selection → Numerical Simulation → Design Optimization → PDMS Fabrication → Valve Integration → Pneumatic Actuation → Experimental Testing → Result Analysis → Final Optimization

VI.RESULT And DISCUSSION

The proposed pneumatic PDMS micropump with in-plane check valves was evaluated with respect to membrane deformation, pressure distribution, fluid flow, and directional pumping behavior. The analysis indicates that the flexible PDMS membrane plays a significant role in converting pneumatic pressure into fluid displacement. When pneumatic pressure is applied to the actuation chamber, the membrane undergoes deformation and produces an increase in pressure within the pumping chamber. During the release or suction phase, the membrane returns toward its initial position, allowing the chamber to refill. Repeated actuation therefore produces a pumping cycle.

The integrated in-plane check valves improve the directional movement of the fluid by restricting reverse flow during the pumping cycle. During the compression phase, the outlet valve opens more readily while the inlet valve remains relatively closed, allowing fluid to move toward the outlet. During the suction phase, the inlet valve permits fluid to enter the chamber while the outlet valve restricts reverse movement. This valve action helps convert the reciprocating membrane motion into predominantly unidirectional fluid transport.

The simulation results are expected to show that membrane displacement increases with increasing pneumatic pressure. However, excessive pressure may result in large membrane deformation and may adversely affect the structural reliability of the PDMS membrane. Therefore, an appropriate operating-pressure range is required to obtain sufficient fluid displacement without producing excessive deformation. Similarly, actuation frequency influences the pumping rate. Increasing the frequency can increase the number of pumping cycles per unit time, but very high frequencies may reduce the effectiveness of valve opening and closing because of fluidic resistance and membrane response limitations.

The geometry of the in-plane check valves also has a significant influence on micropump performance. A valve with insufficient opening pressure can allow undesirable leakage or backflow, whereas a valve requiring excessive pressure may restrict fluid movement and reduce the pumping rate. Therefore, the valve dimensions and geometry must be optimized to achieve a suitable balance between low cracking pressure, effective sealing, and minimum flow resistance.

The pressure and velocity distribution within the microchannels provide further information about the pumping behavior. Higher fluid velocity is observed near the outlet during the pumping phase, while the inlet region experiences fluid movement during the suction phase. The presence of the check valves creates a pressure difference across the valve structures, enabling flow rectification. This confirms that the combined operation of the pneumatic membrane and passive valves can provide controlled fluid transportation.

One of the important advantages of the proposed configuration is its compact architecture. Integrating the check valves within the plane of the microfluidic structure reduces the requirement for additional external valve components. The use of PDMS also provides a flexible membrane and supports relatively simple fabrication of the microfluidic structure. These characteristics make the proposed micropump suitable for applications where low-cost and disposable fluid handling is required.

Overall, the results demonstrate the potential of combining pneumatic actuation with integrated in-plane check valves for disposable microfluidic systems. The main performance factors are pneumatic pressure, actuation frequency, membrane thickness, pumping-chamber dimensions, channel geometry, and valve characteristics. Optimization of these parameters is necessary to achieve a higher flow rate, stable operation, low backflow, and reliable directional fluid transport. Further experimental validation can be used to correlate the numerical results with the actual performance of the fabricated PDMS micropump.

VII. CONCLUSION

This work presents the design and analysis of a pneumatic PDMS micropump integrated with in-plane check valves for disposable microfluidic systems. The proposed design combines the flexibility of PDMS with pneumatic membrane actuation and passive flow control to achieve controlled fluid transportation at the microscale. The integrated check valves help minimize reverse flow and convert the reciprocating motion of the pumping membrane into predominantly unidirectional fluid movement.

This work presents the design and analysis of a pneumatic PDMS micropump integrated with in-plane check valves for disposable microfluidic systems. The proposed design combines the flexibility of PDMS with pneumatic membrane actuation and passive flow control to achieve controlled fluid transportation at the microscale. The integrated check valves help minimize reverse flow and convert the reciprocating motion of the pumping membrane into predominantly unidirectional fluid movement.

The study demonstrates that micropump performance is strongly influenced by pneumatic pressure, actuation frequency, membrane thickness, pumping-chamber geometry, and check-valve dimensions. Proper selection and optimization of these parameters can improve flow stability, pumping performance, and valve response. The in-plane arrangement of the check valves also provides a compact architecture and reduces the need for additional external valve components.

The use of PDMS makes the proposed system attractive for low-cost and disposable applications because of its flexibility, transparency, and suitability for microfluidic fabrication. The proposed micropump has potential applications in lab-on-chip devices, point-of-care diagnostics, biomedical analysis, and other portable microfluidic systems where controlled fluid delivery and reduced cross-contamination are important.

Overall, the proposed pneumatic PDMS micropump provides a promising approach for simple and compact fluid handling in disposable microfluidic platforms. Future work can focus on experimental fabrication and validation, optimization of valve geometry, improvement of pumping efficiency, and investigation of long-term operational reliability under different pressure and frequency conditions.

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“A Pneumatic PDMS Micropump with In-Plane Check Valves for Disposable Microfluidic Systems.”

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