# PMP-NC² - A Bi-Directional, Normally-Closed and Backpressure Independent Micropump

F. Trenkle[1], M. Mayer[2], S. Haeberle[2], S. Messner[2], R. Zengerle[1,2]
[1]Laboratory for MEMS Applications, Department of Microsystems Engineering (IMTEK), University of Freiburg, Georges-Koehler-Allee 103, Germany, trenkle@imtek.uni-freiburg.de
[2]Hahn-Schickard-Gesellschaft fuer Mikro- und Informationstechnologie (HSG-IMIT), Wilhelm-Schickard-Str. 10, D-78052 Villingen-Schwenningen, Germany

**Abstract:**
This paper presents a novel **P**eristaltic **M**icro**P**ump with a twofold intrinsic **N**ormally-**C**losed mechanism (**PMP-NC²**). It is based on a modular concept with a low cost disposable microfluidic chip and a re-usable actuator unit. The normally-closed mechanism prevents fluid flow without power consumption in the stand-by mode for pressures up to 150 kPa. Together with the backpressure independent pumping performance up to 80 kPa this results in a fail-safe and precise micropump. The addressed range of pump rates is up to 100 µL/min. Due to the symmetrical setup, bi-directional pumping is possible and also air bubble tolerance is demonstrated. This results from the very low dead volume per pump chamber of only 230 nL, which leads to a complete transport of the air bubbles through the pump.

Keywords: Microfluidics, Micropump, Microvalve, Normally-closed, Modular, Piezostack

## Introduction

Fundamentals in micropump development started about 20 years ago with the micropump concepts published by van Lintel et al. [1] and Smits [2]. In these early days, Esashi et al. [3] already developed a normally-closed valve and showed the possibility to use a series connection of at least two valves working as a normally-closed micropump. In the following, various micropump concepts have been published, whereas the normally-closed aspect did not receive much attention

Normally-closed micropumps have been described for example by Shinohara et al. [4] and Cao et al. [5]. Shinohara et al. used a silicone rubber structure, clamped between a valve diaphragm and the bottom of the valve chamber to keep the micropump normally-closed up to 50 kPa. The normally-closed micropump concept published by Cao et al. used a silicon boss structure, which is prestressed against the inlet of the pump chamber to prevent fluid flow in the stand-by mode. Nevertheless the proper function has not been shown. Today, normally-closed micropumps are highly recommended to ensure a safe and proper operation, especially when using them as drug delivery devices in medical applications.

## Design

The **PMP-NC²** (**P**eristaltic **M**icro**P**ump – twofold **N**ormally-**C**losed) presented here can be divided into a functional part and a chassis. Fig. 1 shows a front side view (1a), a cross-sectional view (1b) and a back side view (1c) of the functional part. The main components of the modular setup are the re-usable piezostack actuator unit on top, the disposable microfluidic chip in the middle and a re-useable passive actuator in the bottom part (Fig. 1a/b/c). The bottom part has an integrated adjustment mechanism for the vertical alignment of the passive actuator arrangement (Fig. 1b). Additionally, an easy to use ejection mechanism for the microfluidic chip is implemented in the functional part (Fig 1b/c), so that a fast replacement of the microfluidic chip is possible.

The modular setup itself as well as the basic working principle is identical to the previous version of our pump, published in [6]. For better readability it will shortly be summarized in the following: The piezostack actuators are assembled with adjustment parts (o-rings for pre-tension, vertical alignment screws) in a PPS / aluminum casing. The passive actuator features four o-rings and is arranged underneath the microfluidic chip. The microfluidic chip comprises three serially interconnected pump chambers which are confined by a flexible membrane on the top and two orifices (inlet and outlet) at the bottom of each chamber (Fig. 2, left). The three membranes in combination with the orifices in the pump chambers form three serially interconnected microvalves. After insertion of the microfluidic chip, it is pushed upwards towards the plungers of the piezostack actuator unit by the force of the passive actuator. At this, all three flexible membranes are displaced completely into the pump chambers even when the voltage is turned off (Fig. 2, left, 1).

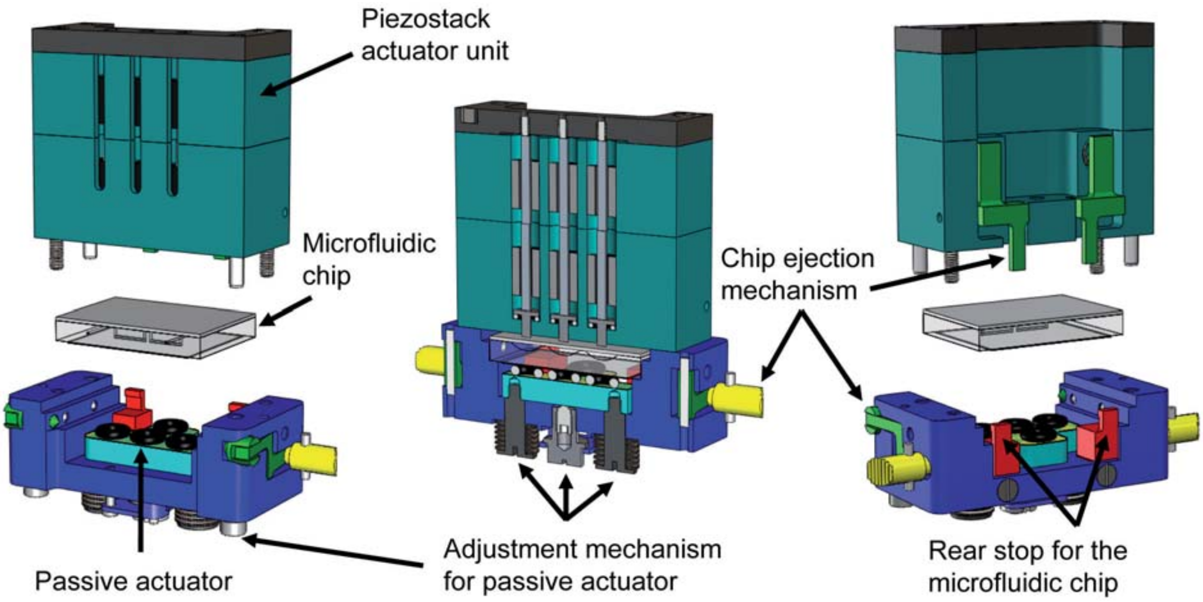


***Fig. 1****: Functional part, showing the modular setup with re-usable actuator unit and disposable fludic chip.*

This way all three valves are closed during stand-by. By choosing proper o-rings the spring constant of the passive actuator unit can be adopted. By setting the screw of the vertical adjustment mechanism the force acting from the passive actuator onto the microfluidic chip can be adopted and leads to a defined prestressing of the three membranes (Fig. 1a/b). The maximum pressure every valve can withstand in its normally-closed state is defined by the prestress of the o-rings and the stiffness of the membranes. This represents and defines the normally-closed property of the micropump. The operation principle of the pump is depicted in Fig. 2. The sequence of the membrane displacements into the three pump chambers are depicted on the left, the sequence of electrical drive signals at the piezostack actuators on the right. Operation starts with applying a voltage to all three piezostack actuators at the same time. This just shifts the microfluidic chip in vertical direction without changing anything else. Sucking fluid into one of the three pump chambers results from a reduction of the voltage at the corresponding piezostack actuator. This way the corresponding membrane relaxes due to its internal reset force and sucks liquid into the chamber. Fluid pumping results from peristaltic operation of those membranes, all details are described in [6]. This way of operation to our knowledge is different to any other piezoelectric driven micropumps published so far.

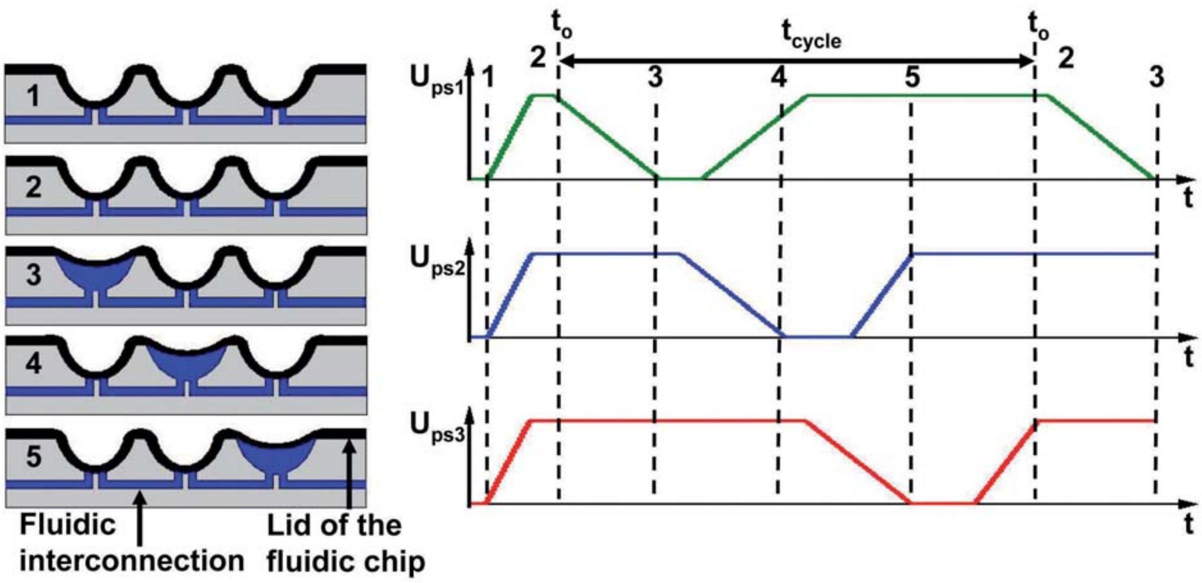


***Fig.2****: Electrical actuation (right) and corresponding states in the microfluidic chip.*

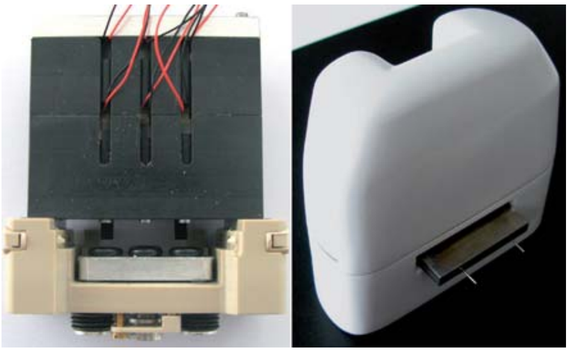

*Fig. 3: Functional part (left) and final assembled micropump showing the microfluidic chip in the ejected state (right).*

During all stages of operation at least one membrane is completely displaced towards the bottom of the corresponding pump chamber, blocking the two orifices there. This way never a fluidic connection between inlet and outlet port of the microfluidic chip exists. As a result displacing the neighbouring membrane leads to a defined volume displacement without any leakage and finally to a backpressure independent pumping performance up to the maximum pressure every valve can withstand in its normally-closed state.
The chassis of the PMP-NC² was just designed for nice appearance and easy handling. Fig. 3 shows a photo of the functional part (left) and the complete assembled micropump with a microfluidic chip ejected by the implemented mechanism (right).

**Fabrication and assembly of the fluidic chip**
The microfluidic chip is fabricated by milling the pump chamber geometry into polycarbonate as described in [6]. In contrast to [6] the membranes contain a central boss structure (5 – 50 µm height, 2.5 mm diameter) which results in a better defined contact surface of the displaced membrane and the two orifices at the bottom of every pump chamber

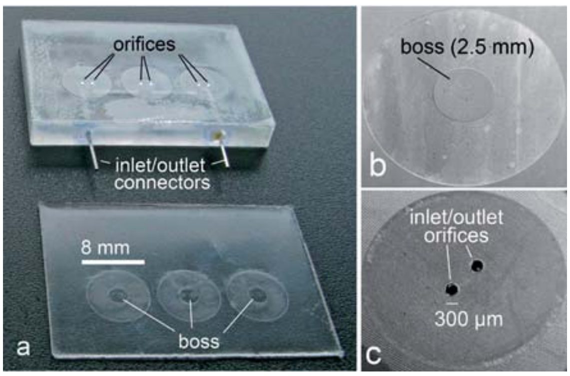


*Fig. 4: Microfluidic chip with structured lid in the front (a); SEM micrograph of the membrane (b); SEM micrograph of the pump chamber bottom (c).*

This way the reproducibility of the normally-closed mechanism and the backpressure characteristics have been improved significantly compared to [6]. Two different materials have been used for the pump chamber membranes, stainless steel and polycarbonate membranes. Fig. 4 shows a photo of a final assembled microfluidic chip with a structured polycarbonate lid in front of the chip (a). The SEM micrographs illustrate the structured boss of the polycarbonate membrane (b) and the pump chamber with the two orifices (c).

**Results**
For experimental characterization of the PMP-NC² we used the laboratory setup published in [6]. We used microfluidic chips with a structured polycarbonate lid having a membrane thickness of 450 µm and a structured boss height of 50 µm. The frequency characteristics of those pumps are depicted in Fig. 5.

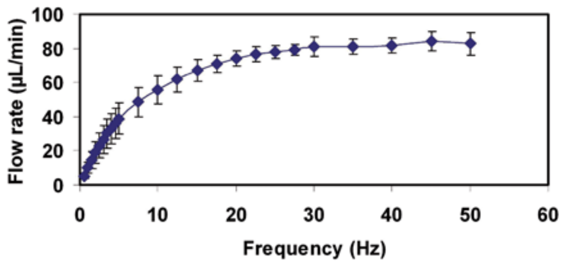


*Fig. 5: Characterization of flow rate versus frequency (error bars are based on five measurements with five different fluidic chips).*

The experimental characterization of the normally-closed feature as well as the backpressure independent pumping shown in Fig. 6 was done by pressurizing a water reservoir against the ambient pressure and connecting it to the outlet port of the micropump. We proofed the micropump being normally-closed up to a pressure of 150 kPa. Backpressure independent pumping was proved to work at a frequency of 10 Hz up to pressures of 80 kPa. Typical limitation was a degradation of the adhesive bond between membrane and chip substrate resulting in leakage. After future optimization of the bonding technology, backpressures significantly higher than one atmosphere should be achievable.
The tolerance of the liquid pump against gas bubbles was investigated by using an optimized version of our microfluidic chip. The dead volume of that chip which is mainly defined by the fluidic channels between the three pump chambers was reduced to 2.5 µL instead of 11µL for the design described before. In addition, our experiments

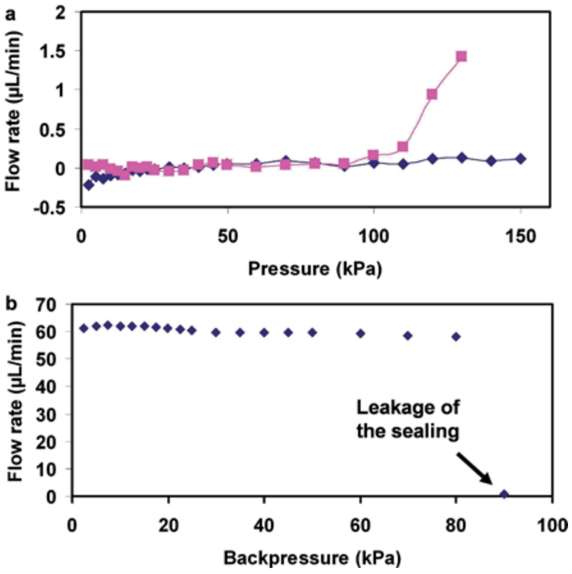


*Fig. 6: Characterization of the normally-closed feature of two different microfluidic chips (a) and of backpressure independent pumping at 10 Hz (b).*

showed that the geometry of the pump chamber is very important for achieving tolerance against gas bubbles. So we reduced the height of the boss on the pump membrane from 50 µm to 5 µm only. This was achieved by electrochemical etching into stainless steel lids with an overall thickness of 120 µm. This way the pump chamber volume was reduced to 0.23 µL. The pump performance after injecting air bubbles of various volumes in the range between 2 – 6 µL is shown in Fig. 7. In fact, the flow rate drops dependent on the volume of the air bubble, but after some time the flow rate recovers to its original value of roughly 100 µL/min. This proves the successful transport of the complete air bubbles through the micropump due to the very low dead volume of the pump chamber (0.23µL). Due to the symmetric design with the three pump chambers in series, the pump direction can easily be reversed by changing the electrical actuation sequence of the three piezostack actuators. The measurements depicted in Fig. 8 shows the liquid flow rate versus operation frequency in forward- and backward direction. Both flow rates are nearly identical, which demonstrates the feature of bi-directional pumping with the presented PMP-NC$^2$ concept.

**Conclusion and outlook**

We presented a novel peristaltic micropump, actuated by three piezostack actuators which is based on the working principle presented earlier in [6]. As a key feature it implies an integrated normally-closed mechanism preventing unintended liquid delivery without power consumption in stand-by mode. Furthermore, the pump is based on a modular setup with a re-usable actuator unit and a low cost disposable fluidic chip. The pump characteristics is exceeding the state of the art in terms of the normally-closed mechanism, and also in terms of backpressure independent pumping over a wide pressure range.

Due to a reduction in the dead-volume of the pump chambers down to 0.23 µL, tolerance against air bubbles could be achieved. The symmetrically build peristaltic pump also allows bi-directional pumping.

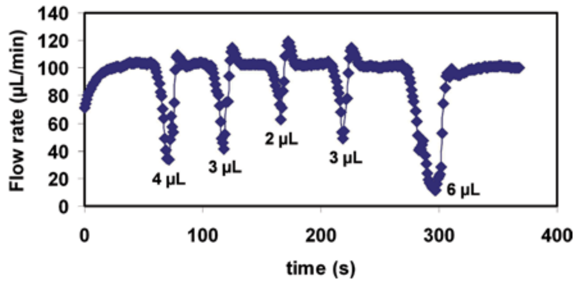


*Fig. 7: Pumping of liquid containing air bubbles of different volumes in the range of 2 to 6 µL at 10 Hz.*

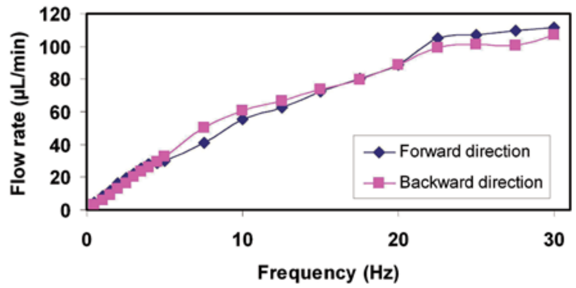


*Fig. 8: Experimental characterization of bi-directional pumping up to 30 Hz.*

Acknowledgement

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