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A self-filling micropump based on PCB technology

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Abstract

This paper presents a novel micropump based on printed circuit board technology (PCB). The pump consists of four PCB layers and one membrane layer forming two passive check valves and one thermopneumatically driven volume actuator. Due to the large deflections of the actuator membrane, the device is completely self-filling and able to pump liquids even with gas bubbles. A maximum flow rate of 530 μl/min (using water) and a back-pressure of 119 mbar are obtained by an average power consumption of 1 W and an exciting frequency of 1 Hz.

Keywords: PCB; Self-filling micropump; Fluidics; Passive microvalve; Thermopneumatic volume actuator

1. Introduction

The development of microsystems for sensing, analyzing and actuating is a necessary and great demand to satisfy the needs of the future society. Only small and powerful systems have the capability to decrease the consumption of resources. Sensors, actuators and electronics have to be combined to realize microsystems. That is why the system integration is essential. The system approach can improve the quality of products on such points as reliability, performance, volume and cost [1].

The PCB technology enables the creation of integrated miniaturized fluidic systems without expensive equipment. Hence, this technology allows a wide introduction of microfluidics even by small companies [2–4].

The technology and the main additional steps to create fluidic elements on PCBs are described in [3,4]. First realized fluidic systems are the pH-regulation system introduced in [5] and the bubble detector described in [6]. This paper, in addition, describes a way to realize flexible parts by introducing a thin polymeric membrane layer between the structured PCBs.

A pump is the essential device in a fluidic system. It generates the drive for fluids (gases and liquids) for its transportation through the system. So far, pumps with thermopneumatic driving principle as well as pumps with stacked non-silicon materials [7,8] have not been integrated yet with electronic circuits. This PCB pump enables the construction of complex integrated fluidic systems containing all necessary electronics to control actuators and processing sensor signals. Thus, this technology is able to provide a valuable contribution for realizing a full system approach in microfluidics.

2. Structure of the micropump

The pump consists of two passive check valves and a thermopneumatically driven volume actuator (cf. Fig. 1). The pump measures 14 mm × 17.5 mm × 3.2 mm (without electronics) in size.

Four PCB layers and one membrane layer are used for the structure. The valves and the actuator use the same membrane for their function. The membrane consists of a thin polymeric foil (Kapton® or Mylar®) which measures 7.8 (Kapton) or 6 μm (Mylar) in thickness. A special adhesive technique is used to connect the structured PCBs and the membrane [2,3]. Due to this technique, the valve seat is coated with adhesive. A slice of Kapton is punched and manually placed on the valve seat before connecting with the membrane to prevent the membrane from sticking on the valve seat.

The heater for the volume actuator is an isolated Constantan® wire (70 μm in diameter). The wire is threaded through small holes (300 μm in diameter) and mounted by soldering. The actuator chamber has a diameter of 10 mm containing air as the working medium.

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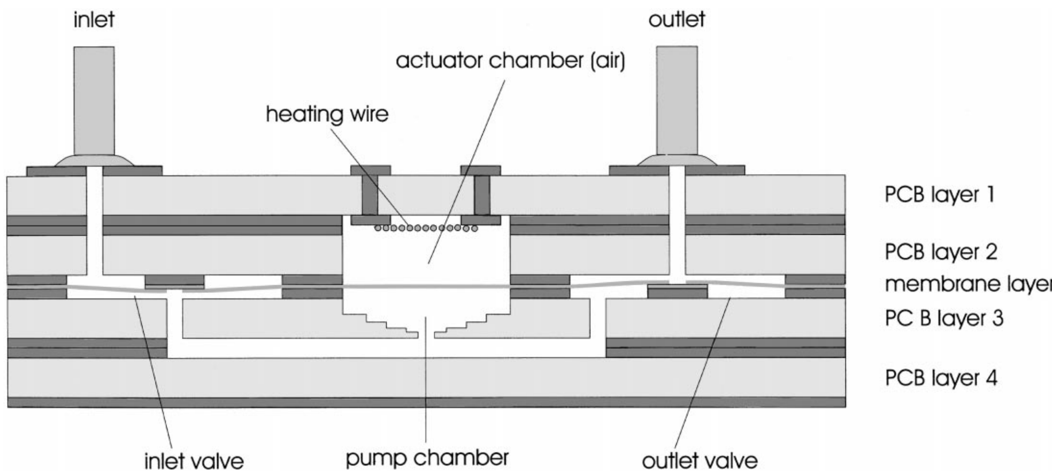

Fig. 1. Schematically cross-section of the micropump.

In order to reach a self-filling capability the dead volume of the pump has to be minimized [8,9]. Therefore, the shape of the pump chamber is adapted to the form of the bulged membrane by use of the milling tool of a Circuit Board Plotter (LPKF). This design step significantly minimizes the dead volume of the pump. Hence, a maximum ratio of the volume compression $\Delta V/V_0$ of ca. 30% (complies to a theoretical pressure rise of ca. 390 mbar) could be reached. This is the reason for the self-filling quality of the pump.

The thickness of the used PCBs is 800 μm. The height of the copper structures measures 70 μm. Drills have a diameter of 300 and 800 μm.

3. Functionality and characterization

The introduction of a flexible layer between the PCBs leads to movable elements with 1 degree of freedom Utilizing these elements, one is able to form actuators and valves.

In order to handle the membrane, it is mounted in a carrying system (clamping rings). This enables the processing of the membrane (drilling, cleaning, coating) and an exact positioning for the connection with the PCBs in a positioning system. By clamping the membrane in the carrying rings, the membrane gets its intrinsic tension.

3.1. Thermopneumatic volume actuator

A sufficient approach for the theoretical dependence between pressure load (p_a) and deflection (w) of a radial symmetric membrane's centre is given by Eq. (1) [10]

$$p_a = \frac{4d\sigma_0}{R^2} w + \frac{8d}{3R^4} \frac{E}{1-v} w^3 \quad (1)$$

where R is the radius of the membrane, d the thickness of the foil and σ_0 the intrinsic tension of the membrane caused by the clamping process, v gives Poisson's ratio and E the Young's modulus of the foil. Fig. 2 comparatively shows a measured and calculated deflection curve of a 7.8 μm Kapton membrane with 10 mm diameter (used values of Kapton: $E = 3$ GPa, $v = 0.34$, $\sigma_0 = 7.5$ MPa).

Fig. 3 schematically illustrates the realized actuator with measurement setup. The actuator chamber encloses air as the driving medium. The chamber forms a closed thermodynamical system.

Assuming air as an ideal gas, a relation between the chamber's increasing mean temperature (ΔT) and the deflection (w) of the membrane is given by Eq. (2)

$$\Delta T = T_0 \left[\frac{p_a}{p_0} \left(1 + \frac{1}{2} \frac{w}{h_a} \right) - 1 \right] \quad (2)$$

where p_a is the pressure in the actuator chamber (cf. Eq. (1)), T_0 and p_0 are determined by the ambient temperature and pressure of the air during fabrication process, h_a the height of the actuator chamber. Fig. 4 depicts the relation in a diagram. The measured values are obtained at thermal equilibrium. The difference to the theoretical curve must be explained due to the decreasing Young's modulus of the polymeric membrane material as a result of the rising temperature and by thermal strain. A temperature rise of 100°C (i.e. ambient temperature plus 100°C) yields a deflection of 350 μm and a chamber pressure of 100 mbar (cf. arrows at Fig. 4). To avoid damages of the PCBs due to thermal stress, the temperature should be kept below 100°C over ambient temperature (because of the adhesive technique).

Closing the actuator chamber during the fabrication at a higher temperature (T_0 of Eq. (2)) yields a negative predeflection of the membrane when cooling down to ambient temperature. This could be used, to take advantage of the high slope of the p–w curve at the small pressure region, e.g. a symmetrical deflection of $\Delta w = \pm 250$ μm requires a pressure difference of $\Delta p = \pm 50$ mbar. These are convenient values compared to $p = +100$ mbar and $w = +350$ μm of only positive directions (cf. Fig. 2). However, this option has not been used yet for the developed pump.

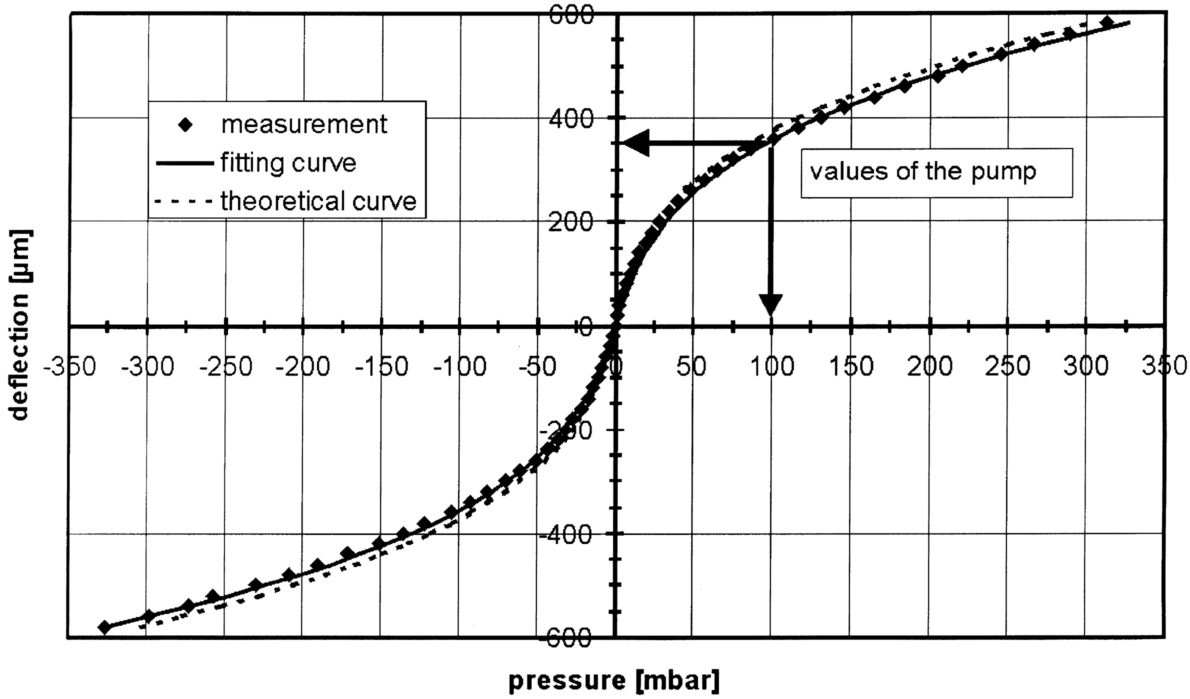

Fig. 2. Deflection curve of a 10 mm diameter Kapton® membrane (thickness 7.8 µm).

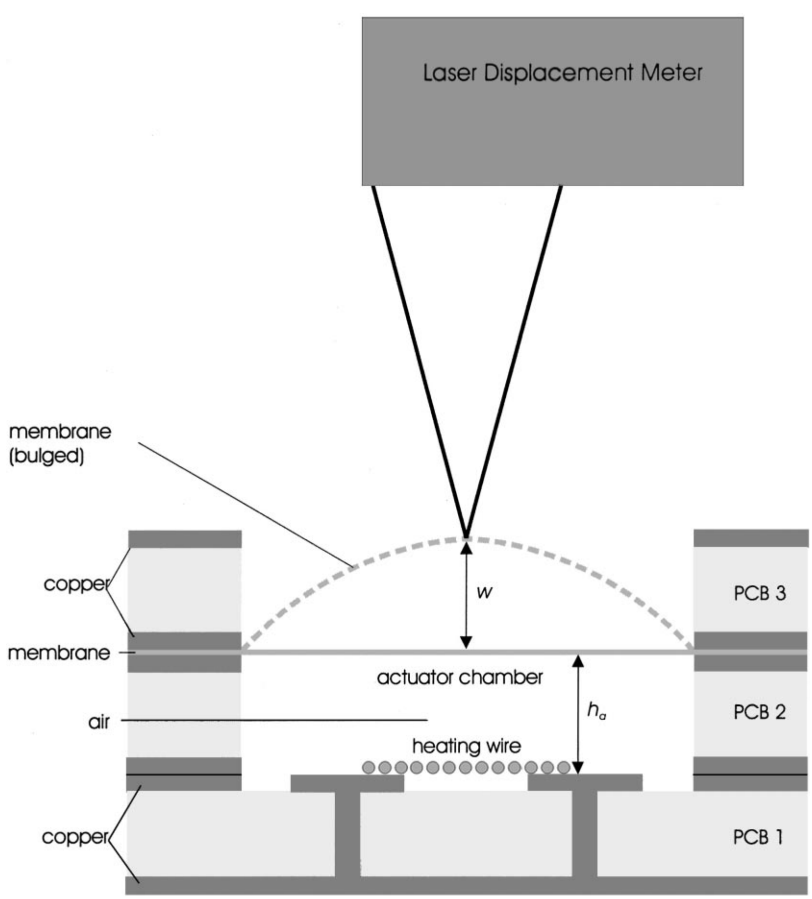

Fig. 3. Schematically cross-section of a thermopneumatically driven volume actuator.

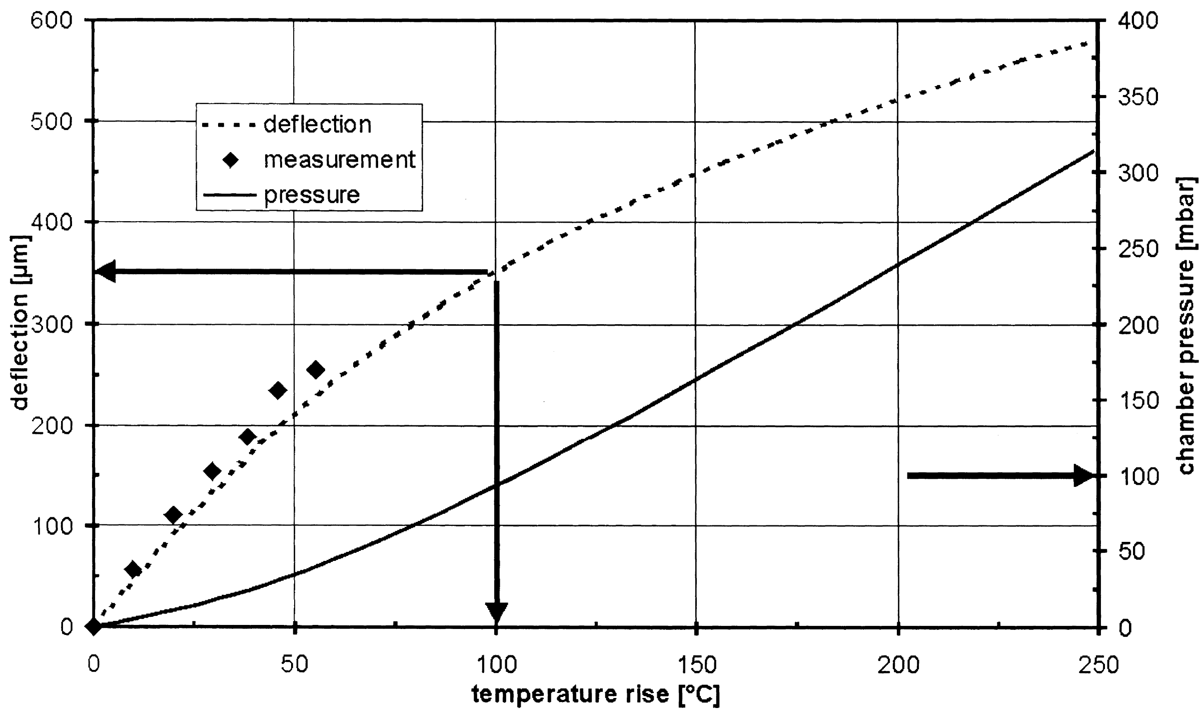

Fig. 4. Theoretical relations of deflection, chamber temperature and pressure of a 10 mm diameter volume actuator and measured deflections at thermal equilibrium.

To observe the dynamic behaviour of the actuator, the membrane's centre of the pressure chamber has been placed under a laser displacement meter (KEYENCE LK-031) (cf. Fig. 3). This experimental setup allows the determination of the system's time constants. Fig. 5 shows a measured deflection curve for a frequency of 1 Hz and a duty cycle of 0.1. The averagely dissipated electrical power was adjusted to 1 W. Deflections of 350 µm were obtained. Therefore, the mean chamber temperature does not exceed the allowed value (cf. arrows at Fig. 4). The cyclic volume displacement and the maximum actuator pressure can be estimated to be 10 µl (parabolic membrane shape $V = 1/2(\pi R^2\,\Delta w)$) and 100 mbar, respectively.

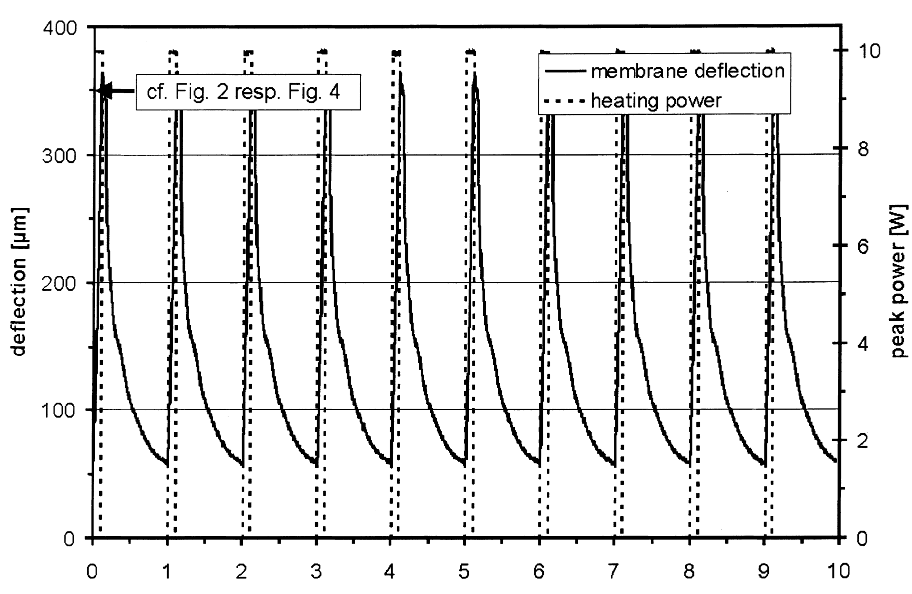

Fig. 5. Dynamically measured membrane deflection of a 10 mm diameter actuator (frequency 1 Hz, duty cycle 0.1, mean power consumption 1 W).

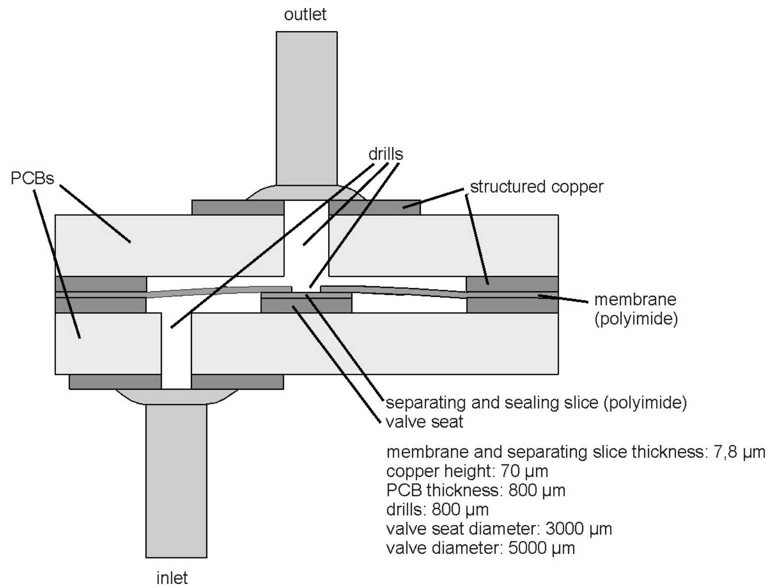

Fig. 6. Cross-sectional scheme of the passive membrane check valve.

3.2. Passive membrane check valve

Fig. 6 schematically shows the cross-section with geometrical data of a single passive check valve. A pressure difference between inlet and outlet controls the flow through the valve. A higher pressure at the valve's inlet forces the membrane to bulge. The valve seat is free and the fluid can pass the valve. In the reverse case (higher pressure at the valve's outlet), the membrane is pressed against the valve seat, so that the flow is inhibited.

Fig. 7 depicts the measured flow rate versus pressure difference. A ratio of over 40 can be reached between fluidic resistance of reverse to forward direction. After overcoming a pressure threshold of ca. 15 mbar (cf. tangent of Fig. 7) the flow linearly rises to the pressure difference. The obtained forward resistance is ca. 9.5 mbar min/ml.

3.3. Pump

Fig. 8 photographically shows the realization of a pump's PCB layer 3 + 4 (cf. Fig. 1). One can see the heating wire over a cooling area in the actuator chamber and the copper structure with drills of a half inlet and outlet check valve. The cooling area is thermally conductive connected (vias filled with solder) to outside (ambient temperature).

For characterizing the pump, the flow rate versus back-pressure has been measured (medium: water). Fig. 9 diagrammatically shows the obtained values. The dissipated electrical power averagely amounted 1 W. The exciting frequency was adjusted to 1 Hz with a duty cycle of 0.1. The maximum back-pressure correlates well with the measured and calculated chamber pressure (cf. arrows at Fig. 2, respectively, Fig. 4).

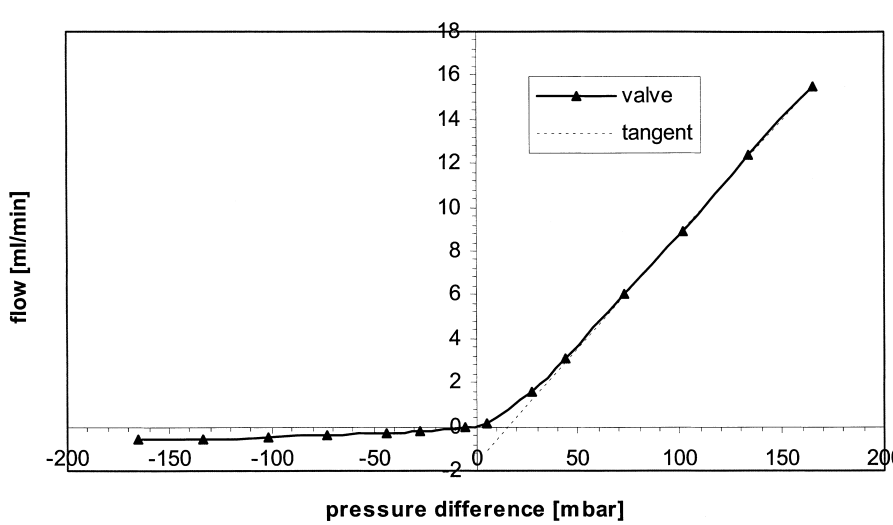

Fig. 7. Characteristic curve of the passive membrane check valve.

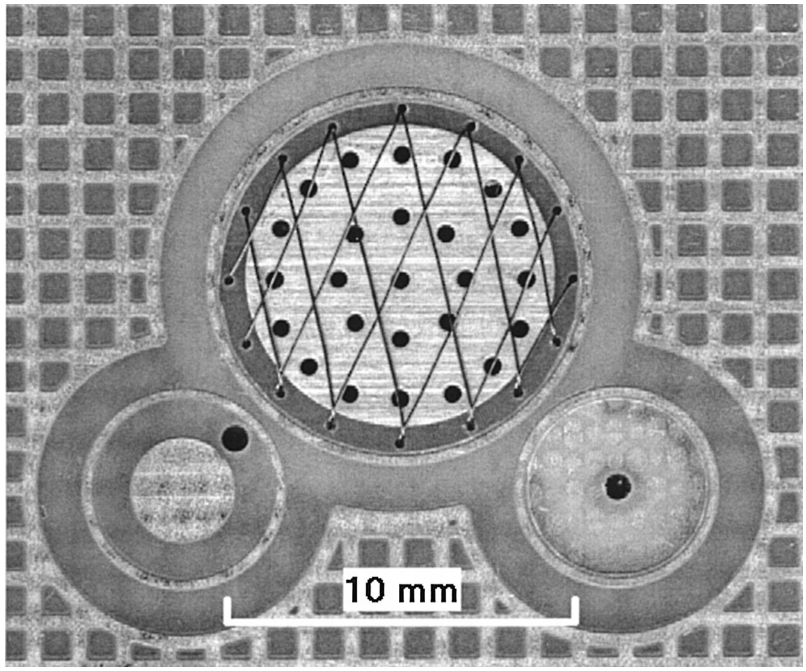

Fig. 8. Photographically view of the pump layers 3 + 4 (cf. Fig. 1).

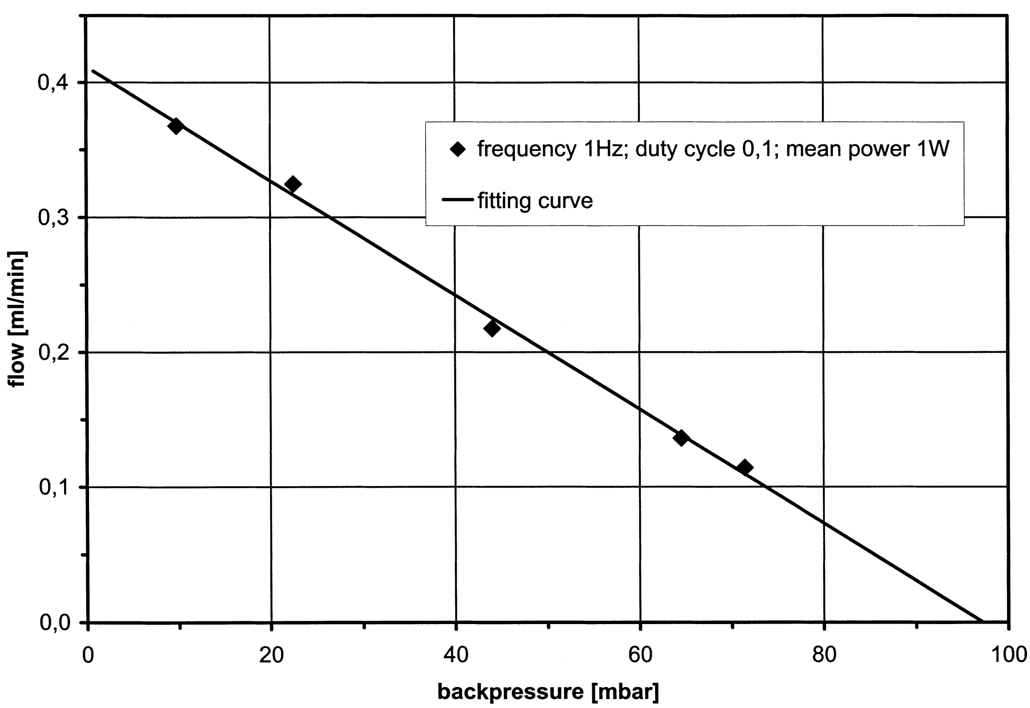

Fig. 9. Characteristic pump curve.

Measuring the flow rate versus the exciting frequency at constant pulse width yields the diagram of Fig. 10. A peak flow of 0.66 ml/min is received with a frequency of 1.8 Hz (duty cycle 0.18; average power consumption 1.8 W). First duration tests over 540,000 pump cycles (more than 150 h) without any failure and loss of capability lead to the supposition of a high working reliability.

4. Conclusions

The developed micropump shows the capabilities of microfluidics based on PCB technology. This pump is the key for really independent integrated fluidic systems on PCBs. A lot of applications are possible, e.g. a complete supporting system for biological cell cultures.

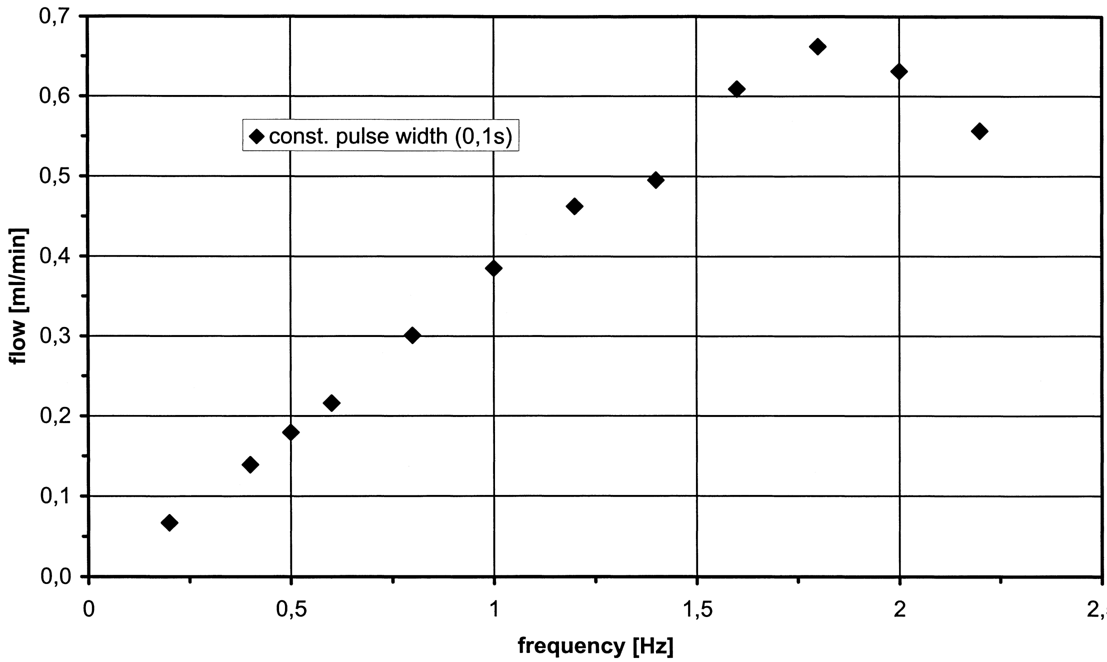

Fig. 10. Flow vs. exciting frequency for constant pulse width (0.1 s).

The developed fluidic PCB technology makes the integration of any desired fluidic structure easily possible. Mixing, delivering, dosing or measuring of properties of fluids are very suitable tasks for the integrated fluidic PCB systems. For example, to increase the pump performance (flow rate or back-pressure) an array of several pumps could be interconnected on one PCB and used simultaneously.

The big advantages of utilizing the PCB technology for microfluidics are the simple and cheap technological equipment and materials needed for the fabrication (compared to silicon and LIGA technology) and the chance of integrating possibilities.

Acknowledgements

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Biographies

Ansgar Wego was born in 1971 in Rostock, Germany. From 1994 to 1999 he studied Electrical Engineering at the University of Rostock. Since 1999, he joined the Graduate College "Integrierte fluidische Sensor–Aktor-Systeme" at the University of Rostock doing doctoral studies. His main interests are device development for fluidic systems.

Lienhard Pagel has been Professor in Microsystems and Director of the "Institute of Electronic Appliances and Circuits" at the University of Rostock since 1994. Prior to this he worked in research and development in the semiconductor industry for 10 years. Since 1994, his main topic has been the realisation of microfluidics systems in PCB technology.