RECENT DEVELOPMENTS IN MICROSYSTEMS FABRICATED BY THE LIGA-TECHNIQUE

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Abstract

As an example of microsystems fabricated by the LIGA-technique three systems are described and characterized: a triaxial acceleration sensor system, a micro-optical switch and a microsystem for the analysis of pollutants. The fabrication technologies are reviewed with respect to the key components of the three systems: an acceleration sensor, an electrostatic actuator and a spectrometer are made by the LIGA-technique, a micropump and microvalve are made using micromachined tools for molding and optical fiber imaging is made possible by combining LIGA and anisotropic etching of silicon in a batch process. These examples show that the combination of technologies and components is the key to complex microsystems. The design of such microsystems will be very much facilitated if standardized interfaces are available.

Introduction

At the Research Center in Karlsruhe (FZK), the LIGA technology (Bec86) as one of the dominant micro patterning technologies has been developed over the last ten years. Three years ago, the promising economic perspective of microsystems has led to an increase of FZK's activities in this field by coordinating the work from areas such as patterning technologies, chemical sensor fabrication, assembly, material science, electronics and computer science.

In this paper, the results of our efforts on three microsystems will be reviewed as an example of the activities of FZK:

- a triaxial acceleration sensor system in a planar setup consists of two LIGA-acceleration sensors for the detection of acceleration within the substrate plane and a commercially available silicon acceleration sensor for the direction normal to the substrate; this setup simplifies assembly tremendously;

- a switch for monomode fiberoptical communications uses an electrostatic LIGA-actuator on a silicon substrate with etched grooves for vertical placement of lenses and with LIGA lateral fixing elements for lenses and fibers;

- a microsystem for the optochemical analysis uses a LIGA-spectrometer with especially designed electronics and a micropump for fluid control to and from a micro cuvette which carries optochemical sensors..

In the next section we will give a brief review of the involved technologies and we will describe the key components of the microsystems. Subsequently, the microsystems and their performance will be described.

Microstructure Technology and Components

The fabrication procedure of microcomponents usually involves all of the three technologies: patterning, material deposition or etching and microassembly. Full batch fabrication is the goal since it promises high repeatability, good quality control and high output per processed substrate. All the technological steps of the LIGA-technique (x-ray lithography, electroplating and molding) are batch processes. Though molding of these structures has been successfully implemented (Bot 94, Mül 95) it will not be covered here since mass fabrication is hardly an issue for space applications and for small numbers of structures x-ray lithography and electroforming is more economic than to setup LIGA molding facilities.

To fabricate acceleration sensors as well as electrostatic actuators the LIGA-process has been improved by a sacrificial layer technique. The process scheme is shown in *Figure 1.* Before the PMMA x-ray resist is cast onto the substrate, an electrical layer of Cr/Ag and a sacrificial layer of Ti are patterned by optical lithography and wet etching. After x-ray exposure and development, the PMMA pattern is filled by electroplating, Ni is used for the acceleration sensor but Ni/Fe permalloy, Cu or Au are also available as a standard. When the resist has been stripped, the sacrificial layer is etched away and finally the substrates are diced and the individual sensors are mounted and bonded onto the circuit board (Moh 90) using the Cr/Ag bond pads on the substrate.

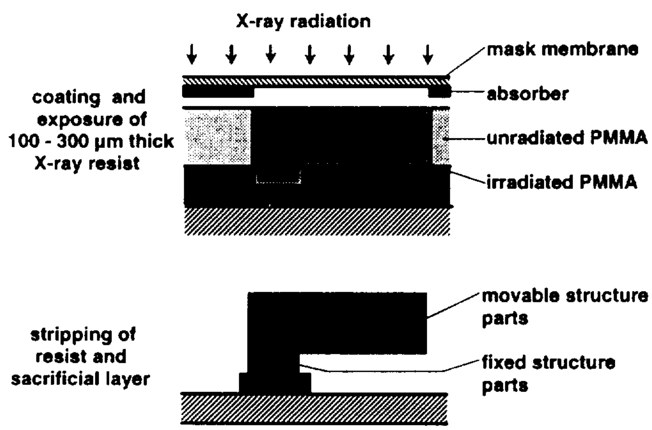


Figure 1: Process Sequence for the Fabrication of Moveable LIGA Microstructures (sacrificial layer technique)

Figure 2 shows the schematic of the LIGA acceleration sensor where the moveable seismic mass forms two capacitors with the adjacent fixed electrodes. The final design is shown in an SEM picture in Figure 3. The smallest lateral dimension is the width of the capacitor gaps which is merely 4µm and which results in a high zero acceleration capacitance of 4.5pF. The height of the structure of 200µm requires special attention with respect to the development process (Elk 94). The complete sensor is 3mm long and 1mm wide. The mass is suspended with two parallel cantilever beams to two stationary blocks (on the right side). They assure a parallel deflection of the seismic mass which is favorable for high linearity. The width of the beams determines the sensors' maximum acceleration range which may be between 1 and 20g, depending on the design. Four fixed blocks in the corners of the structure prevent a short between the seismic mass and the fixed electrodes. The fixed electrodes are interrupted every 100µm for two reasons: first, during processing, the corresponding PMMA bar stabilizes the 4µm thin PMMA wall which forms the capacitor separation and, second, the width of the interruptions may be used to tune the damping coefficient of the structure depending on the atmosphere to 0.7 as desired for maximum bandwidth. The complex forked geometry of the seismic mass ensures that the capacitance of parts for which the gap width decreases with temperature is identical to parts for which the gap width increases with temperature (Str 93). Figure *4* shows that the linear term of the temperature dependence is completely suppressed by the forked design. Table 1 summarizes the experimental data of a 1g LIGA-sensor element (Str 94).

Table 1: Experimental Data of the LIGA-Acceleration Sensor (Str 94)				
sensitivity	resonance frequency	damping coefficient	thermal zero shift	thermal shift of sensitivity
20%/g	557Hz	0.45	$6*10^{-5}$g/K	$2.3*10^{-4}$/K

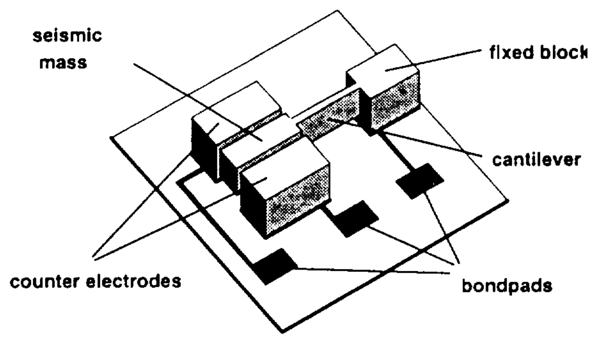


Figure 2: Schematic of a LIGA Acceleration Sensor.

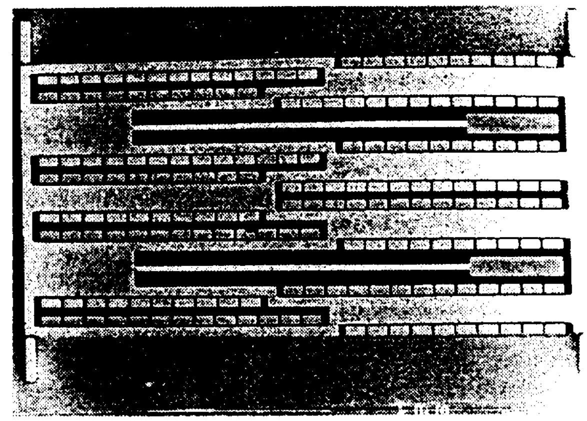


*Figure 3: SEM-Picture of an Optimally Designed Sensor Element. Overall dimensions are 3mm*1mm. For details see the text.*

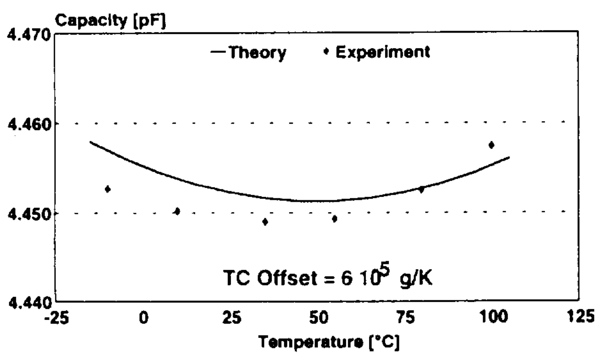


Figure 4: Temperature Dependence of one of the Sensor Element's Capacitances.
A strong linear term which may result from different expansion coefficients of the substrate and the electroplated nickel is completely compensated for by the forked design (Str 93)..

The electrostatic linear actuator shown in Figure *5* has been especially developed with respect to large displacements (Moh 93). *Figure 6* shows the individual teeth in an enlarged way. From Figure *7* it can be seen that a design with parallel plates has a limited displacement of 70µm because for this design the electrostatic force remains constant while the spring force increases. For large displacements, the conical design uses also the force component that rises as $1/d^2$ where d is the separation of the plates. Fabrication tolerances result in an unsymmetric placement of the slider by 1µm. The $1/d^2$ component of the force not only pulls the slider in the desired direction but also onto the sides. For small displacements, this component can be compensated by springs that need to be designed stiffly in this direction but at higher displacements, guiding elements are required that prevent the slider from contacting the electrodes. When the guiding elements are touched (≈ 190µm), friction leads to a drastic decrease of the net force.

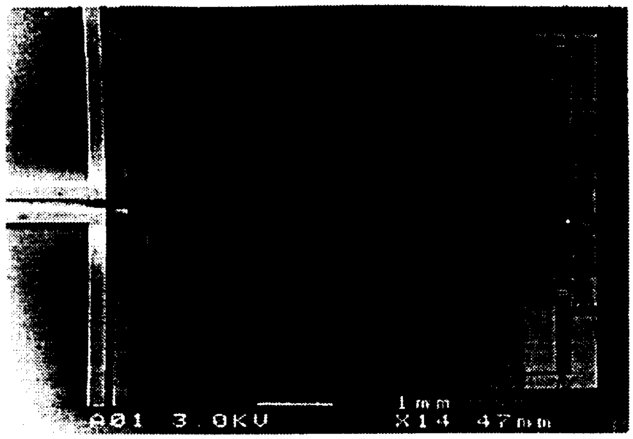


Figure 5: Electrostatic Linear LIGA-Actuator Optimized for Large Displacement.
On the left side, the fixing elements for fibers can be seen. Parallel cantilever springs on the left and right ends of the actuator are used to hold and guide the slider. They need to be stiff with respect to a side motion of the slider (vertical in the picture)(Moh 93).

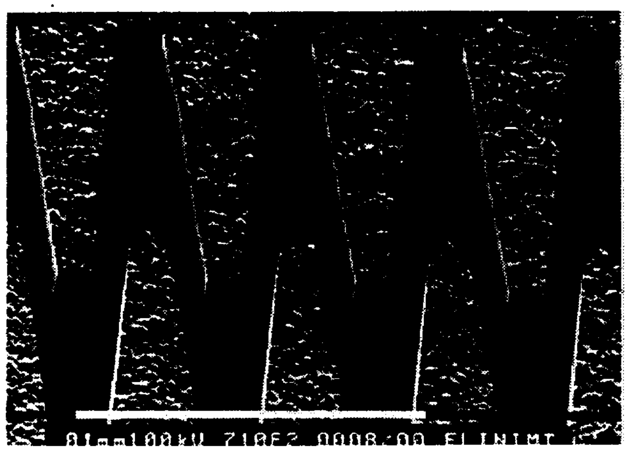


Figure 6: Close-Up View of Individual Capacitor Elements.
The cone angle is 15°. A parallel design referred to in Figure 7 has a cone angle of 0°.

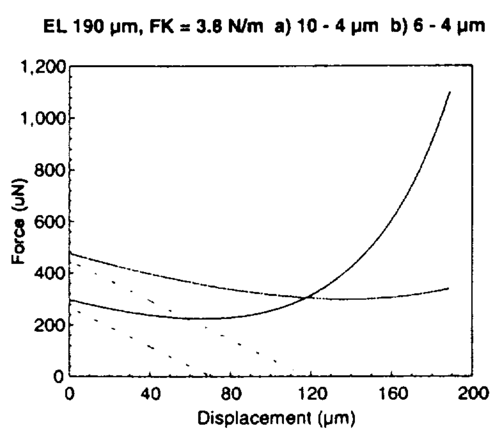


Figure 7: Calculated Force-Displacement Characteristic of the Conical Actuator (70V).
The dashed lines correspond to a parallel plate design with (constant) plate separation of 10µm and 6µm for the lower and higher forces, respectively. The full lines correspond to the conical design with the same initial plate separations.

To fabricate a blazed spectrometer, we use a 3 layer x-ray resist consisting of PMMA as a core-layer and PMMA and a copolymer as cladding layers which are bonded to each other by high pressure welding at temperatures slightly above the glass transition temperature. The transition zone between the layers is approximately 10µm thick (Göt 91). The core layer has a higher index of refraction and guides the light coupled into the structure by a multimode fiber (Figure *8*). By a fiber connector, a clear optical interface is defined. Figure *9* shows part of the grating whose step height is 0.2µm at a step length of 3µm and a vertical height of 125µm which corresponds to the thickness of the fiber. The fabrication of this structure is a technological challenge in all process steps involved: mask making, x-ray exposure and development and, for mass fabrication, molding. Further details can be found in (Mül 94).

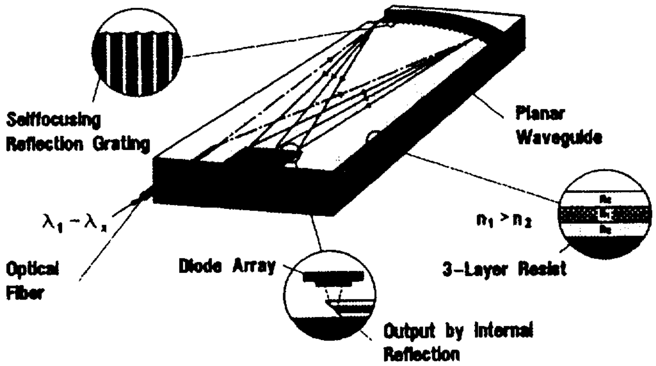


Figure 8: Principle of the LIGA-Microspectrometer. The light is transferred to the device by an optical fiber and is guided by the core layer. A slanted sidewall is used to reflect the light out of the device onto a linear CCD diode array.

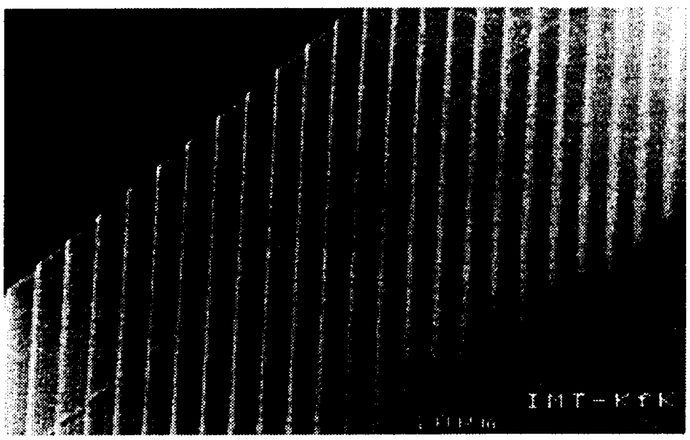


Figure 9: Close-Up View of the Spectrometer's Teeth.
The interface between the core and cladding layer is clearly visible. The step height is 0.25µm, their length is 3µm. The sharpness of the teeth extends over the whole resist height of 175µm (Mül 93).

In order to measure the intensity of the diffracted light, a slanted sidewall of the PMMA structure is used to direct the light out of the spectrometer plane (Figure *8*). This makes the alignment of a linear CCD-diode array with a pixel size of 25*500µm very easy. An evaluation board which includes ADCs, a microcontroller and a serial port has been developed and has been fabricated in SMD multilayer technique. The complete set-up fits into a box of 70mm*60mm*15mm. The experimental data of the spectrometer are listed in Table 2.

Table 2: Characteristic Data of LIGA-Microspectrometer

spectral range	transmission at λ_{blaze}	spectral resolution	attenuation to scattered light	optical fiber	diode array	dynamic range	measuring time
400-1100nm	25%	7nm	25dB	50/125µm gradient index	Hamamatsu S5464-512F	10000 - 20000	40ms - 2560ms

Besides x-ray lithography, micro milling and drilling has evolved as an important patterning technology to fabricate molding tools (Bie 93). As shown in Figure *10*, several levels may be fabricated with smallest dimensions being limited by the available tools: 50 µm diameter for a drill and 300 µm for a micro-end mill. To fabricate pneumatic devices for example a pump (Büs 94) or an active valve system (Fah 94) such tools have been extensively used to mold the casings from PSU. Their fabrication also requires thin-film deposition, optical lithography and adhesive bonding. Particularly adhesive bonding had to be developed and the main contribution has been the development of aligned adhesive bonding for batch processing using capillary forces in order to deposit the adhesive in the desired places (Maa 94).

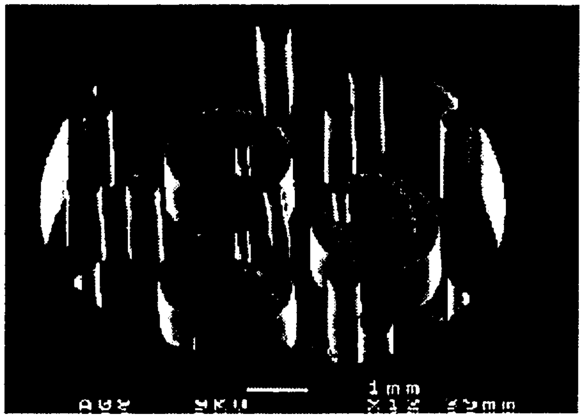


Figure 10: SEM-Picture of a 4 Level Molding Tool Fabricated by Micro Milling and Micro Drilling.
The smallest dimensions are holes of 50µm and the width of areas where material has been removed can not be smaller than 300µm. The limitations result from the dimensions of the smallest commercially available tools (Fah 94).

The micropump shown in Figure *11* is made of two PSU casings between which a polyimid membrane is placed. The polyimid membrane seals the actuator chamber and by pulsed resistive heating, the air volume underneath the actuator chamber is displaced. Two passive valves are used to obtain a directed flow of the displaced gas. With these pumps, flow rates in the range of 220µl/min can be achieved at a pulse rate of 30Hz (Table 3).

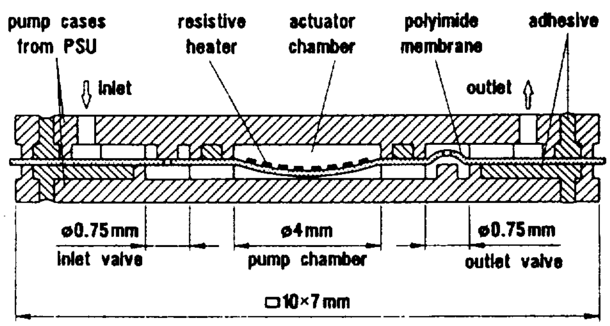


Figure 11: Schematic of a Micropump for Gases.
The fabrication makes use of thin-film technology, optical lithography, molding and adhesive bonding (Büs 94).

Table 3: Characteristic Data of the Micropump for Gases

drive voltage	max. outlet pressure	max. flow rate	pulse length	pulse frequency	dimensions
15V	130 hPa	220µl/min	2ms	30Hz	$10*7*1mm^3$

Triaxial Acceleration Sensor System

Since acceleration is a vector, it needs to be measured in all three directions of space. This can be accomplished by using two LIGA-sensor elements for the directions perpendicular to the substrate normal (Str 94) in combination with a silicon sensor element for the normal direction. With this planar set-up little or no alignment of the sensor elements is necessary since the LIGA-structures may be processed orthogonally by design on a single substrate and the third direction is the natural direction of sensitivity of the silicon sensor. Figure *12* shows the completed sensor system including hybrid electronics and digital signal processing.

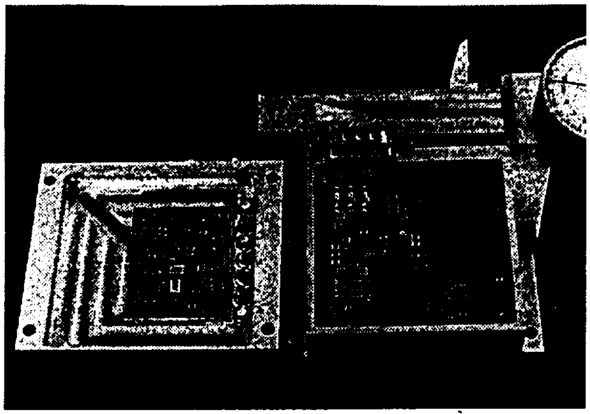


Figure 12: Complete Triaxial Acceleration Sensor System.
Two LIGA-Sensors measure within the substrate direction, one silicon sensor measures the normal direction. On the left side, the sensor elements and the analogue board, on the right side ADCs and digital electronics for preprocessing and external communications are shown.

The key to low-cost and efficient sensor systems are sensor elements with high linearity and low thermal drift because for such an excellent sensor element, expensive corrections of the data are not necessary. In order to preserve the good characteristics of the LIGA-acceleration sensor element, a hybrid feedback read-out circuit has been developed. It uses controlled electrostatic forces to keep the seismic mass centered between the fixed electrodes. It has been optimized with respect to a high 3dB bandwidth and low noise. Table 4 summarizes the experimental results obtained with this circuit. It should be noted that the current resolution limit (1.2μg/√Hz) is due to the mechanical noise of the equipment and that the bandwidth includes zero frequency (DC) as well. Table 4 summarizes the characteristic data of the sensors. A system that has been extended to obtain redundancy and that includes data preprocessing has been described in (Stro 94).

Table 4: Characteristic Data of 2g Acceleration Sensor Element with Feedback Readout

range	sensitivity	linearity	thermal zero shift	resolution	3dB frequency
2g	1971mV/g	0.8%	90μg/K	28μg (1.2μg/√Hz)	570Hz

Microoptical Bypass Switch

In optical communications, a device is needed to bypass a faulty user or amplifier. The electrostatic actuator shown in the previous section fulfills three major requirements: the LIGA sidewall has a very small roughness so that it can be used as a mirror, the displacements are somewhat larger than the diameter of a collimated fiber beam and no energy is required to keep the actuator at any position. For monomode applications, an optical bench is required that images the fiber ends onto each other. The schematic of Figure *13* illustrates the principle. Since imaging with ball lenses of the diameter of the fibers (125μm) is physically prohibitive, commercially available ball lenses of 900μm diameter have been used. This makes the fabrication of the system more complex because a major requirement is to have the optical axis parallel to the substrate surface within very narrow tolerances (Mül 93). By anisotropic etching of (100) silicon wafers, the lenses may be positioned vertically with the required level control of less than 1μm. For the lateral fixing of the lenses a LIGA resist pattern is used (Figure *14*). The precision of the lateral position of the fixing elements is strongly dependent on the stresses that bend the whole substrate during processing. For the most influential process steps, sputter deposition and electroplating, special parameters had to be found that minimize this stress. The coupling losses of the optical part has been measured in a separate set-up. They vary between 1.6 and 2.4dB of which almost 1dB may be attributed to reflection (Mül 95). The measured values are well within the requirements of 3dB for this system. The complete system that includes the actuator is currently being investigated experimentally.

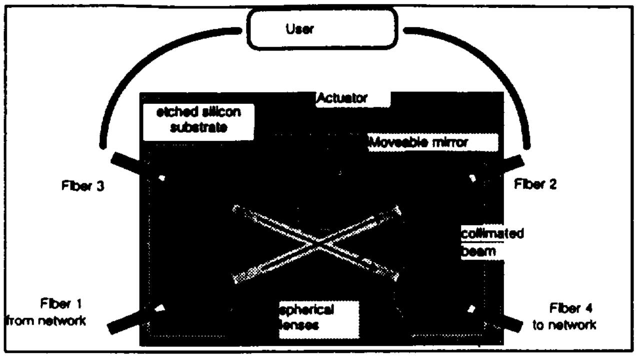


Figure 13: Schematic of the Bypass Switch. In the active mode which is shown, the signal proceeds from fiber 1 to fiber 4 via the user and an amplifier. In the inactive mode, the signal is coupled directly from fiber 1 via the mirror to fiber 4 (Mül 95).

Figure 14: SEM-Picture of a Lens Leveled by an Etched Silicon Substrate and Fixed by LIGA-Structures.

Microsystem for Optochemical Analysis of Pollutants

Figure *15* shows the schematic layout of a microsystem for optochemical analysis of heavy metal ions in water. It consists of a module of 4 micropumps for fluid handling, a microcuvette with chemical sensors on its sides, the LIGA-spectrometer to measure the extinction over the whole wavelength range and a 16 bit µ-controller to control the micropump and the data transfer to a PC. The 4 pumps are working in a special sequence so that a reference liquid as well as the sample liquid are pumped through the microcuvette. To avoid contamination of the pumps with liquids, they are working as pressure or vacuum pump.

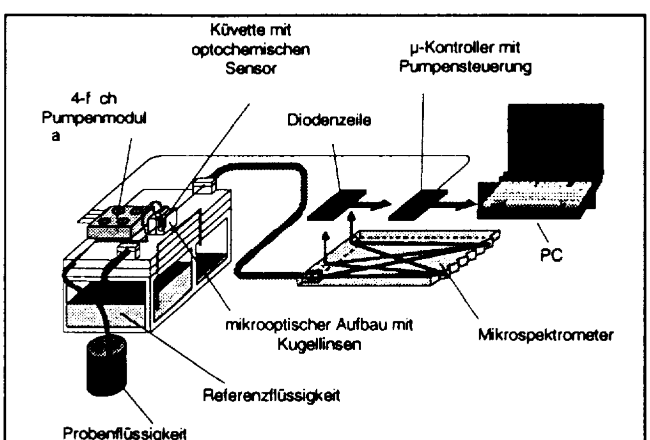
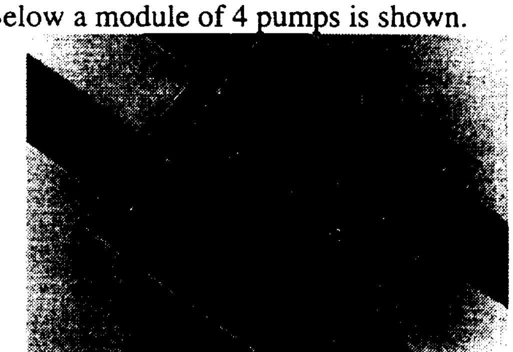


Figure 15: Principle of the Optochemical Analysis System.
Below a module of 4 pumps is shown.



The optochemical sensors change their transmission behavior depending on the concentration of Hg, Pb, and Cd. A multicomponent analysis has been realized by using derivatives of porphyrin so that different metal ions show different absorption coefficients in different spectral ranges (Rec 93). The following limits of detectability have been measured:

Hg(II)	30μg/l
Cd(II)	1μg/l
Pb(II)	20μg/l

Long time stability has been considerably improved by binding the porphyrin to a macromolecular carrier with a molar weight of 60000. At constant concentration, the sensor signal decays by merely 15% over a time period of 40 days (Rec 93).

Conclusions

In the past, the efforts in microtechnology have concentrated on different fabrication technologies and on components compatible with these technologies. The LIGA-technique is most important because the large structural height is advantageous with respect to actuator forces, the extreme sidewall smoothness makes optical applications possible and the small structural detail may be exploited in diffraction optics.

The microsystems presented here clearly indicate that the technologies and components are sufficiently advanced in order to design real systems. It has been shown that future improvement is expected by combining different technologies, for example LIGA and silicon-etching or LIGA and micromachining. To facilitate this, a major prerequisite for the near future is the definition of standardized interfaces between components fabricated by different technologies.

Acknowledgments

The microsystems presented here have been mainly developed during the last three years. Many people have contributed to the design and to their successful fabrication. The authors would like to thank the coworkers of the Karlsruhe Research Center who are named in the references. Their cooperation in submitting figures and photographs is gratefully appreciated. The authors would also like to express their deep gratitude to the technical personnel who have contributed to the fabrication of the actuators through all these years.

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