Modular Concept for Fluid Handling Systems
A demonstrator Micro Analysis System

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ABSTRACT
A modular planar concept for fluid handling microsystems is presented. The concept is based on a planar Mixed Circuit Board with electrical and fluidic interconnections acting as a substrate for sensor and actuator modules. Several modules realised within this concept are presented, and the design as well as modelling and simulation of the fluidic components and systems is discussed. Furthermore, the general application of this concept in micro analysis systems is considered. Finally, the modular concept is demonstrated by a micro chemical analysis system containing micro-pumps, flow sensors, an optical absorption cell and control electronics.

INTRODUCTION
Over the past few years there has been an increasing interest in the development and realisation of miniaturised total analysis systems (µTAS) [1-3]. This growth is partly due to the rapid developments in fluid handling devices such as micropumps, -valves, -filters and -mixers [4], but is also explained by the need for complex (bio)chemical sensor systems with integrated self-test and calibration features. This has led to attempts to fabricate miniaturised flow systems [2,3] and microfabricated parts for separation systems [5-7]. However, since such systems typically would comprise a variety of components, materials and technologies, considerable attention should be paid to the integration-concept of such systems. The two extreme forms of integration are hybrid and monolithic. An example of a completely hybrid analysis systems is the stacked phosphate analyser by Van der Schoot et al [2], whereas the liquid dosing system of Lammerink et al. [8] is an example of a monolithic system. In practice, most systems will consist of a combination of these two forms. The concept we propose here enables a modular mixed integration of different system components or subsystems on a planar backplane: the Mixed Circuit Board. This MCB serves at the time as mechanical support for the system components (modules), it has the necessary electrical connections (Printed Circuit Board) and contains the microchannels for fluid transport connecting the different modules (Channel Circuit Board).

Flow Injection Analysis (FIA) is a commonly used method for the quantitative determination of a variety of chemical compounds [9]. In several publications the potential advantages of miniaturisation have been indicated [10,11]. Thus, FIA is an attractive method to be incorporated in a demonstrator system. In this study a very simple chemical system, acidification of the pH-indicator Congo-red, is taken as an example to demonstrate the performance of the system concept.

MCB CONCEPT
Figure 1 shows schematic diagrams of the Mixed Circuit Board which generally consists of two parts to form the fluid channels. The MCB could be built by a glass-
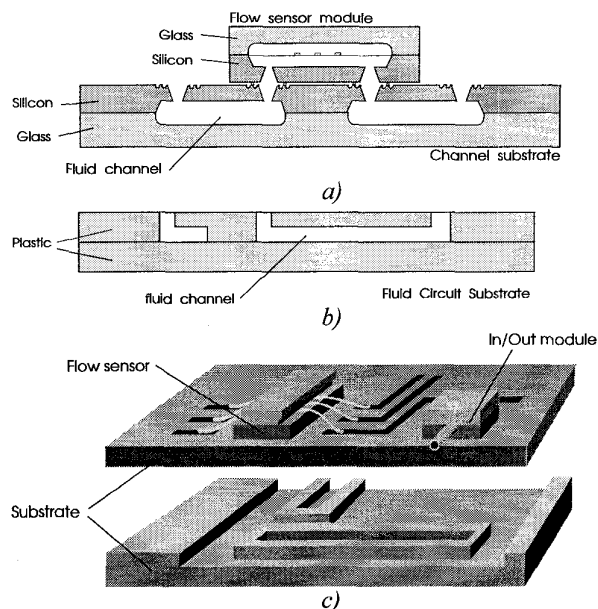

Figure 1. Planar modular concept for fluid handling micro-systems with functional modules on top of a Mixed Circuit Board.
a) Flow sensor on top of a silicon- glass MCB,
b) MCB made of plastics,
c) 3D-view of MCB with flow sensor and input/output module.

silicon sandwich but also by plastics. The modules can be attached with the help of existing bonding techniques like anodic bonding, glue, soldering etc. The demonstrated MCB consist of an epoxy Printed Circuit Board attached to a transparent polycarbonate substrate. Versions with machined channels in either one or the other part are used.

The top surface of the MCB contains the electric connections and holes for fluid transport from and to the channels. Future developments of the MCB similar to the developments in the Printed Circuit Board technology like flexible versions are feasible. The planar concept facilitates, rather than vertical stacks [12], high volume 'pick and place' production processes.

SYSTEM MODULES

For the realisation of fluid handling microsystems a wide variety of modules is needed. Many of them, like pumps, flow sensors and filters, were already developed before, but for integration into the modular system new designs have been made. In figure 2 to figure 6, SEM and/or
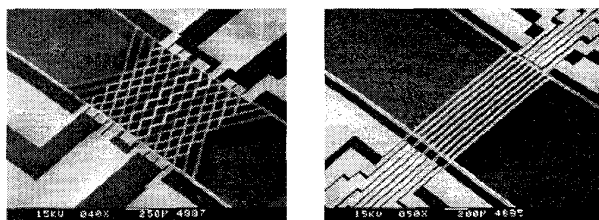
a)   *b)*

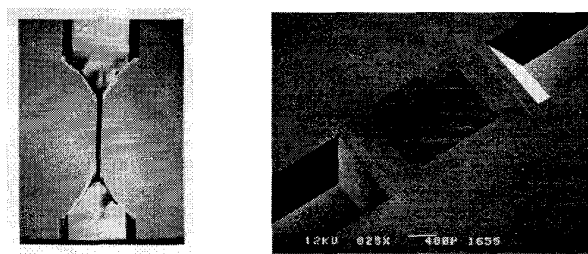*Figure 2. a) Grid type flow sensor, b) beam type flow sensor (the fluid channel width is 1 mm).*

a)   *b)*

Figure 3. a) Hydraulic resistor made of anisotropically etched V-groove and b) mixer and/or filter module.
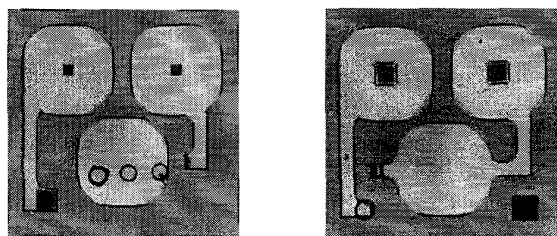
a)   *b)*

Figure 4. a) Micropump (top) and b) micropump (bottom).
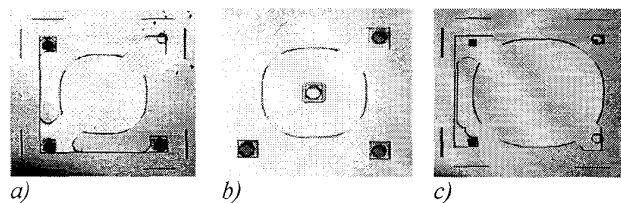
a)   *b)*   *c)*

Figure 5. a) Top view of pressure controlled valve (two hydraulic resistors also visible), b) bottom view of pressure controlled valve with valve ridge visible [13], and c) hydraulic capacitor-resistor combination.

optical photographs of several realised system modules are shown. These are all based on the standard fluid port pitch of 5 mm.

APPLICATIONS

Miniaturised FIA-systems can be used for a variety of applications. First of all, such systems can be used to replace existing conventional FIA-systems, operated by roller-pumps. In that case the direct advantage is a 10-100 fold reduction in reagents and sample consumption [2].

A second application is as an autonomous instrument for environmental field measurements. The aforementioned advantages are here accompanied by a low power consumption, enabling a long stand-alone time with battery use. In the medical sector, miniaturised FIA systems can be used for bed-side monitoring or (continuous) patient monitoring; in both cases the small size is an important feature. An example of such a microsystem is given in figure 7.
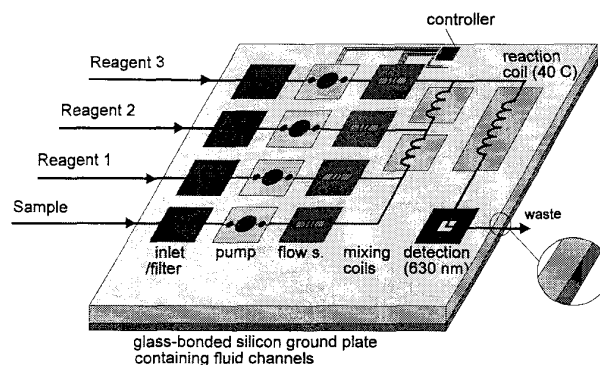
Figure 6. Ammonia analysing system according to the proposed MCB-concept.

Finally, in space applications the low weight accompanied by the small size gives the system a decisive advantage over conventional systems. In addition to the mentioned advantages, the use of silicon processing may also give lower fabrication costs. This is, however, strongly dependent on the type of system and, especially, the production volume.

MODELLING AND DESIGN

Because of the enormous diversity in components it is difficult to describe a straightforward design-path for components for the MCB concept. Here we focus on the modelling and the design of the fluid control modules and specific on the thermo-pneumatic actuated micropump used (twice) in the demonstrator. An elaborated model of this micropump is given by van de Pol et al. [14]. Main functions of the fluid control in micro analysis systems are the switching function and the direct flow and/or pressure control. Building blocks are hydraulic inertances, resistors, capacitors and passive and control-valves. Very often an active element like a micropump is needed.

The approach we have in adapted in our group is based on finite element modelling (FEM) in combination with lumped element modelling. FEM is used for specific (mono-)domain problems. Although the encountered geometry's can be rather complex, FEM is not the appropriate tool for modelling the whole system (multi-domain) behaviour. The FEM modelling results in specific lumped parameters (e.g., stiffness, capacitance, fluid resistance) which are subsequently used in a lumped element system model. This lumped element system modelling and simulation tool is based on the bond graph description language. Practical implementation of the modelling and simulation is done using the 20SIM program package [15]. As an example for this approach, the modelling of a thermopneumatic micropump is given. Simulation results as well as design aspects of a microsystem containing two of these micropumps are discussed.

Thermo pneumatic micropump

The demonstrator analysing system contains two thermo-pneumatic actuated micropumps (see figure 7). The micropumps are of the reciprocating type and consist of three main building blocks: a thermo pneumatic actuator (A), a pump chamber with a flexible pump membrane which acts as a capacitor (C), and two passive circular silicon check valves (V), see figure 8.

The pump actuator generates a periodically varying pressure in the air chamber. This pressure acts on a flexible pump membrane between actuator and pump chamber. Due to the deflection of the pump membrane, the volume of the pump chamber changes. By means of two check valves, the liquid is periodically sucked in through one valve and forced out through the other valve, thus forcing a flow into one direction.

The thermopneumatic actuator consists of a cavity filled with air and a thin film heating resistor supported by thin
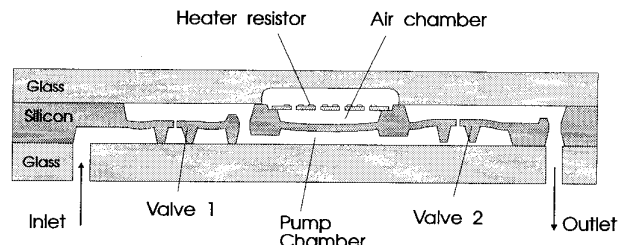

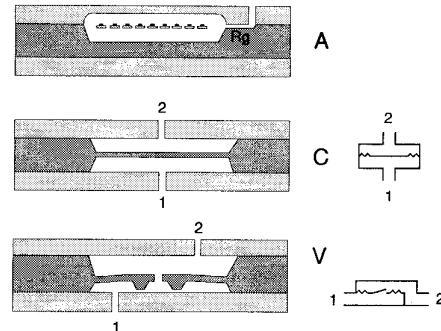Figure 7. Cross section of thermopneumatic actuated micropump used in the demonstrator.

Figure 8. Cross sections of the glass-silicon-glass structures for the pump actuator, the pump membrane and the valves. Right from the figures, the Ideal Physical Models (IPM's) of the pump membrane and the valve are given.

silicon nitride beams for (periodically) heating the gas inside. A narrow air channel connects the cavity to the outside and allows a pressure exchange with the surroundings. A typical actuator does have a circular air chamber with a diameter of 8 mm and a height of 400 μm with the resistor mounted in the middle between 'floor' and 'ceiling'. The 'thermal' response (warming up and cooling down of the air) can be described with a 'thermal' relaxation time τ_t which is mainly determined by the heat capacity of the heater-resistor and the heat conductivity of the gas [14]. A second relaxation time is determined by the heat capacity of the whole pump body and the heat conductivity of the body to its surroundings. Due to the air channels there is also a (third) 'pneumatic' relaxation time τ_p. Since the pneumatic system is non-linear, τ_p can only be approximated. A simulation of the actuator behaviour is given in figure 9.

The pump membrane acts as a capacitor (see figure 8, C) which stores a volume, related to a pressure drop. In first approximation the volume change under the membrane is linear with the centre displacement [13]. The membrane capacitance, however, shows a strong non-linear behaviour for centre displacements in the range of large deflections. Simulations of the stored volume in the pump membrane as a function of the pressure difference across the membrane are given in figure 10.
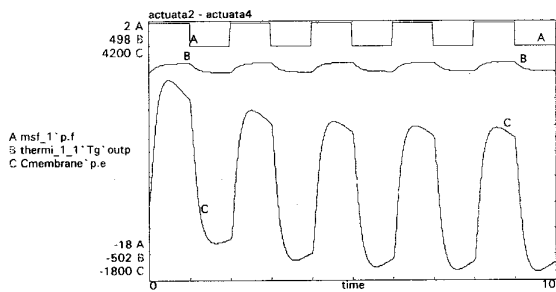
Figure 9. Simulation of a pump actuator: A = heating power in [W], B = gas temperature in [K] and C = gas pressure in the actuator chamber in [Pa]. The thermal relaxation times are 0.2 and 200 [s] and the pneumatic relaxation time is 2 [s].
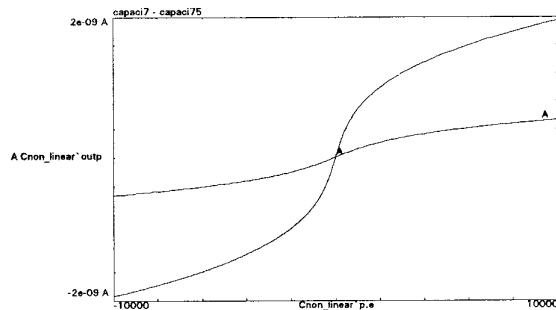

Figure 10. Simulation of the stored volume in the pump membrane $[m^3]$ as a function of the pressure difference across the membrane [Pa]. Si-membrane diameters are $d = 0.01$ [m] and $d = 0.007$ [m], membrane thicknesses are $2.5 \ 10^{-5}$ [m].

The normally closed check valves consist of a flexible outer ring and a rigid inner sealing ridge (see figure 8, V). When pressure p_1 is higher than p_2, the sealing ridge is lifted, and liquid flows through the valve. When pressure p_2 is higher than pressure p_1 the valve is closed. Due to a thin oxide layer on the valve ridge the valve has a small pre-pressure. Obviously, the valve has a strongly non-linear behaviour. The simulation results for the stored volume in the valve and the flow through the valve are given in figure 11.
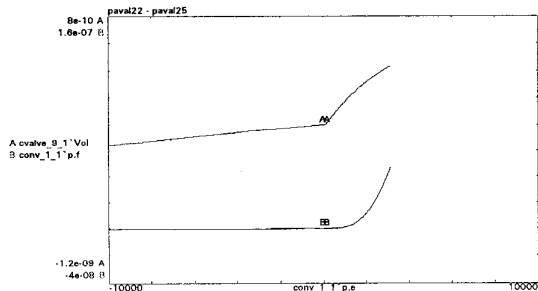

Figure 11. Simulation of the stored volume A $[m^3]$ and volume flow B $[m^3/s]$ of a check valve as a function of the pressure difference [Pa] over the valve. The Si-valve membrane diameter is 8 mm and the membrane thickness is 25 µm.

A bond graph model of the whole micropump is given in figure 12. The pump is driven by a (square-wave) heat source. Because the basic building blocks of the pump are modelled as sub-models, the topology of the bondgraph model is very similar to the pump structure given in figure 7. Simulation results of the whole pump are given in figure 12 and figure 13.
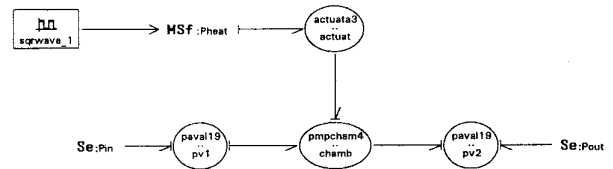

Figure 12. Bond graph model of a thermopneumatic actuated micropump. The submodels refer to the basic building blocks as given in figure 8.
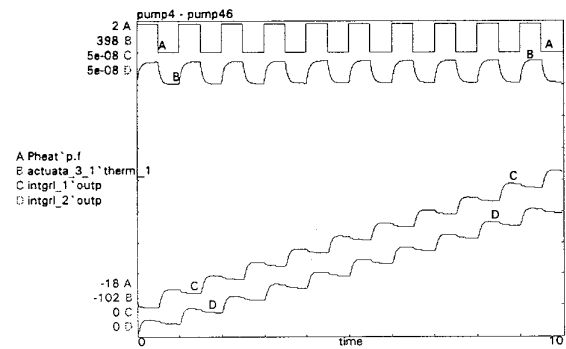

Figure 13. Simulation results of a thermopneumatic actuated micropump. A = power dissipated in the heater in [W], B = temperature of the air in the actuator chamber [K], and C, D = (integrated) flow in the input and the output of the pump (trace C has an offset of 1/10 full scale).
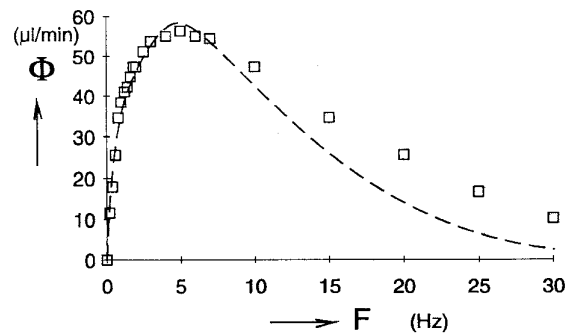

Figure 14. Simulated and measured [8] pump rate as a function of the excitation frequency. The amplitude of the simulation is fitted with the amplitude of the heating power.

Using the bond graph description language, modelling of more complex systems becomes relatively simple. The simulation model as well as the simulation results of the demonstrator system with two micropumps are given in figure 15 and figure 16.
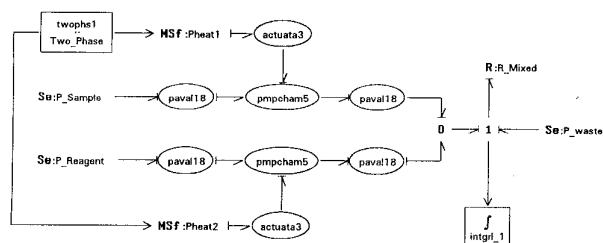
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Figure 15. Bond graph model of demonstrator analysing system during mixing stage with both pumps working in anti-phase.
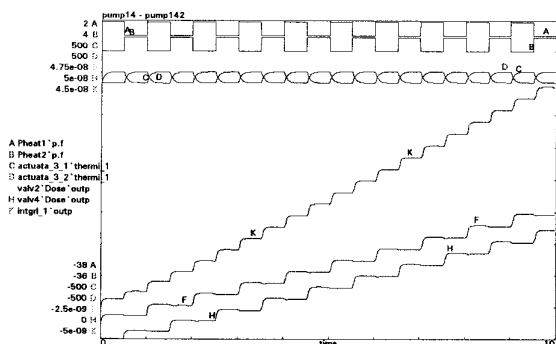

Figure 16. Simulation results on demonstrator analysing system with two pumps working in anti-phase. A, B= heating power in [W] to the pumps; C, D = actuator gas temperatures [K]; F, H = pump yields in $[m^3]$ (F has 1/20 full scale offset); K = total dose through the detector.

DEMONSTRATOR SYSTEM

A schematic diagram of the demonstrator chemical analysis system is given in figure 17. The MCB comprises three in/outlets, two micro-pumps, two flow sensors and an optical absorption detector module.
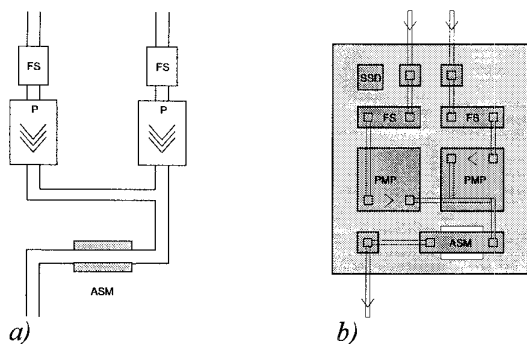

a)   *b)*

Figure 17. Micro Analysis System. a) Structure of MAS with two flow sensors, two pumps and an absorption sensor module. b) Component lay-out of MAS.

The purpose is to measure chemical reaction products by detection of the (spectral) absorption intensity. Sample

and reagent liquids are mixed in the appropriate amounts on-board (currently the actual mixing takes place during the propagation in channels) and the optical absorption is measured at the detector side.

The electronic control circuitry is situated in two levels below the MCB layer with the modules. It is based on a microcontroller system for the micro liquid handling and the chemical analysis data. Implemented in the electrical circuitry are driving circuits for the micro pumps, sensing circuits for the flow sensors, optical absorption measurement circuitry, power management and communications using an RS232 interface.

The absorption cell is a glass silicon glass sandwich component (15x1x0.4 mm) where optical intensities from different coloured LED's are measured by a 64 pixel CCD detector, see also figure 18.

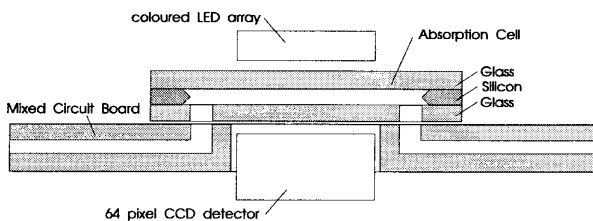An overview of the demonstrator system with a total system volume of about 50 ml is given in figure 19.

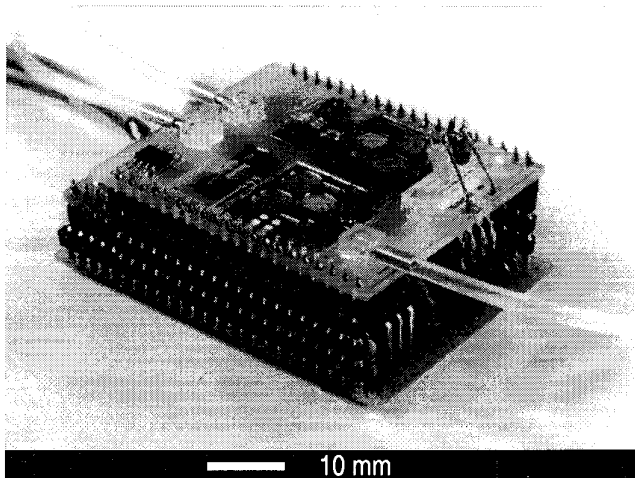*Figure 18. Cross-section of the optical absorption detector.*

Figure 19. Demonstrator MAS modules mounted on a MCB.

RESULTS

Figure 20 shows test results of the measured pump and flow sensor behaviour. The time constant of the pump/flow sensor combination is in the order of 0.2 sec. This is in accordance with the simulation results. Integration of the flow sensor signal results in a very smooth dose function.
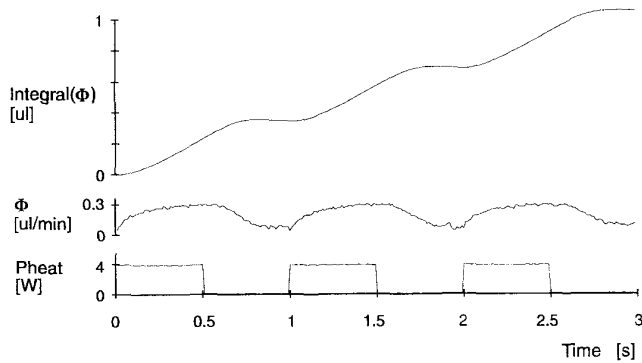
Figure 20. Measured pump and flow sensor behaviour.

The operation of the absorption detection is demonstrated by recording absorption intensities. This was done at four different wavelengths for three liquids: a transparent fluid, the Congo red indicator at pH=7 (red-coloured), and the Congo red indicator at pH=3 (blue-coloured). In agreement with the literature the red LED detector shows the largest extinction, see figure 21.
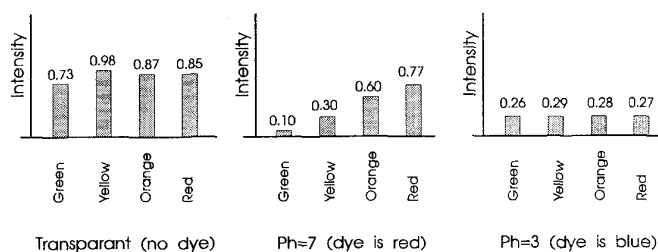

Figure 21. Measured light intensities with four coloured LED's.

CONCLUSIONS

A modular concept for fluid handling microsystems is proposed. Several system components are fabricated within this concept, implementing standardised electrical and fluidic connections.

Models for the component and system behaviour are developed and verified by experimental results. Bondgraph modelling and simulation proved to be an effective tool in designing microsystems.

A demonstrator chemical analysis system (μFIA-system) comprising two micropumps, two flow sensors, an optical absorption cell and control electronics is designed, simulated and fabricated.

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[15] 20SIM, Commercially available modelling and simulation package developed at the University of Twente, Control laboratory, Faculty of Electrical Engineering, Enschede, the Netherlands.