EWOD SYSTEM DESIGNED FOR OPTICAL SWITCHING

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ABSTRACT

This paper presents the design and experimental characterization of a microfluidic system comprising a novel bi-phasic liquid combination actuated by EWOD (electrowetting-on-dielectrics). The two immiscible liquids feature a high difference in refractive indices (0.16−0.23) and a low absorption (<4.3 dB/cm) in the telecommunication wavelength range (1260−1650 nm), which open up new application fields for microfluidics. Utilizing the presented fluidic design, a bi-stable, non-volatile switch is implemented for optical waveguide couplers. The droplet movement is demonstrated with liquid combinations exhibiting specifically chosen refractive indices.

INTRODUCTION

Electrowetting is a flexible method to move and manipulate droplets with the aid of electric fields in the micro- and nanoliter range. Despite excessive research over the past decades in the field of EWOD, the focus was mainly on droplet liquids with high relative (rel.) permittivity, but without digging deeper into specific optical properties. Water or ionic aqueous solutions enclosed in an ambient liquid of non-conductive oil are still the most extensively used liquid combinations, because of the strong electrowetting effect and stable immiscibility [1, 2]. Ionic liquids (salts in liquid state) are also often used in EWOD setups [3]. The melting point of these liquids is usually above 0°C and therefore not suitable for non-conditioned outdoor systems that require a wider temperature range, e.g. -40°C to 70°C. Chevalliot et al. presented a list of non-aqueous liquids for display applications with standard silicon oil as ambient liquid [4]. For optical telecommunication systems, low absorption in the wavelength (λ) range from 1260 nm to 1650 nm is required. No systematical research on this topic has been published so far.

SYSTEM DESIGN

Working principle

An optical coupler can change its state by altering the refractive (refr.) index of the cladding [5], which can be implemented by a two-phase liquid system. A defined difference in the refr. indices of the liquids is a key factor for the functionality of the switch. The liquid medium covering the coupler can be changed with very low power consumption via electrowetting if the liquids exhibit the appropriate electrical properties. Besides finding a liquid combination with suitable optical and electrical properties, the goal of this work is to design a bi-stable, non-volatile switch, i.e. the bar- and cross-states of the switch can be maintained without energy consumption. Therefore, a fluidic barrier is implemented into the fluidic design to ensure physically stable droplet positions.

The optical part of the system (optical chip) is fabricated by thin film technology [5] and is not discussed in this contribution. In the following an electrowetting based microfluidic system (fluidic chip) is described and tested to solidify the feasibility of the bi-stable, non-volatile switching concept.

Table 1: Target properties of the liquids.

Properties	Ambient liquid	Droplet liquid
Refr. index (λ = 1260 −1650 nm)	difference of 0.16	
Permittivity (<10 kHz range)	low	high
Contact angle (CA) on FDTS/PTFE	<90°	>90°
Dynamic viscosity [mPas]	low	low
Boiling point	>70°C	>70°C
Melting point	<-40°C	<-40°C
Vapor pressure	low	low
Density	minor difference	

FDTS: Perfluorodecyltrichlorosilane
PTFE: Polytetrafluoroethylene

Liquid selection

To guarantee a short optical coupler switch with low crosstalk and insertion loss over the whole telecommunication wavelength range, a minimum difference in refractive indices of the liquids of about 0.16 is required. From the perspective of EWOD and microfluidics additional liquid requirements have to be fulfilled (see Table 1).

The novel bi-phasic EWOD system presented here consists of

- diphenyl sulfide (DPS, CAS No. 139-66-2) or
- triphenyl sulfide (TPS, CAS No. 2974-10-9)

as non-conductive ambient liquid and

- ethylene glycol (EG, CAS No. 107-21-1) or
- hydroxy propylene carbonate (HPC, CAS No. 931-40-8)

as electrowetting-active, polar, high permittivity liquid. They fulfill the complex requirements of the proposed concept. The relevant measured properties of the chosen liquids are listed in Tables 2 and 3. The CAs and dynamic viscosities were measured by the authors and the refr. index by CommScope Inc, each at room temperature (20°C).

Table 2: Properties of the ambient liquids.

Properties	DPS	TPS
Refr. index (λ = 1550 nm)	1.60	1.64
Rel. permittivity (<10 kHz range)	5.43	as DPS
CA on FDTS/PTFE in air [°]	85/84	as DPS
Dynamic viscosity [mPas]	4.2	25.3
Boiling point [°C]	296	461.5
Melting point [°C]	-40	-28
Vapor pressure [Pa]	1.0@25°C	3.92e-6
Density [g/cm³]	1.11	1.23

Table 3: Properties of the droplet liquids.

Properties	EG	HPC
Refr. index (λ = 1550 nm)	1.41	1.44
Rel. permittivity (<10 kHz range)	37	109.7
CA on FDTS/PTFE in air [°]	97/99	99/103
CA on PTFE in DPS [°]	160	130
Dynamic viscosity [mPas]	16.1	85.4
Boiling point [°C]	197.3	354±15
Melting point [°C]	-12.9	-69
Vapor pressure [Pa]	8	2.6e-4@25°C
Density [g/cm³]	1.113	1.4

Additional properties are extracted from public databases which apply for room temperature and atmospheric pressure (10^5 Pa), unless otherwise noted.

Fluidic chamber and electrode design

The developed layout of the fluidic chip is shown in Figure 1. Its chamber geometry is based on the publication of Blankenbach et al. in 2008 [6]. The first prototype consists of four cells, one per optical coupler, to obtain a 2x4 strictly non-blocking optical switch. After injecting the ambient liquid, the cells can be filled individually with the droplets by a pipette tip through the sandblasted openings in the glass chip. Each droplet has a volume of around 65 nl, is 0.9 mm in diameter and each cell is equipped with four electrodes separated by 20 µm gaps. Backflow channels are integrated into the sidewalls supporting the dynamic switching mechanism. As shown in Figure 2, the droplet can be moved through the fluidic barrier in both directions by EWOD actuation. As a result, the refractive index changes in the opened cladding of the optical coupler (optically active area). Voltage is only applied to change the state of the switch.

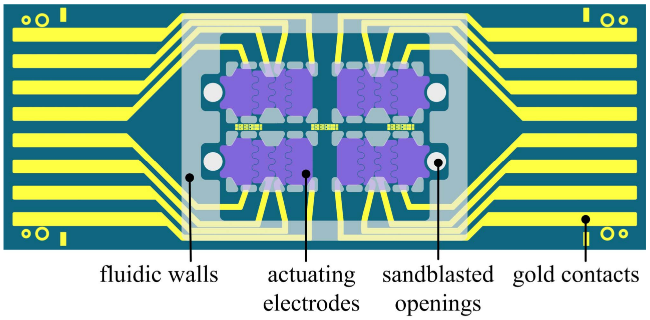

Figure 1: Top view of the fluidic chip design with overall size of 4.5×12 mm².

The fluidic and optical chips are placed in a crossed configuration so that both the optical and the electrical contacts can be established conveniently, see Figure 3.

Fabrication technology

The cross section of the functional layers is illustrated in Figure 4. The structure is based on Eagle XG® glass wafers (500 µm thickness) carrying ITO (indium-tin-oxide) electrodes for liquid actuation. The electrodes are structured by a wet chemical etching process. The fluid channels are made of Ordyl SY 300 permanent dry film resist laminated on the substrate in two layers with a total thickness of 100 µm. A chrome-gold thin film double layer is deposited and wet etched which enables the electrical connection between the ITO electrodes and the PCB. The fluidic structures are uniformly coated with an Exilis® dielectric layer (300 nm) and PTFE as dewetting layer (50 nm) in a low temperature chemical vapor deposition process.

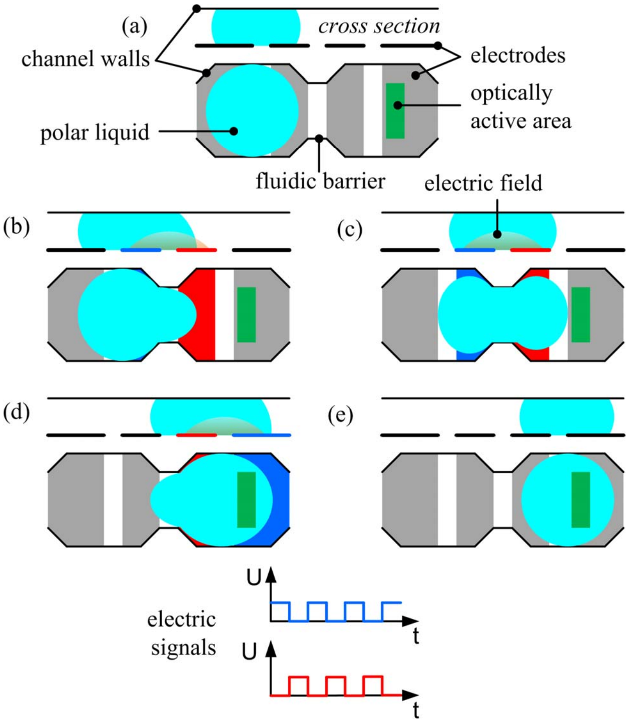

Figure 2: Actuation sequence with four electrodes in a cell.

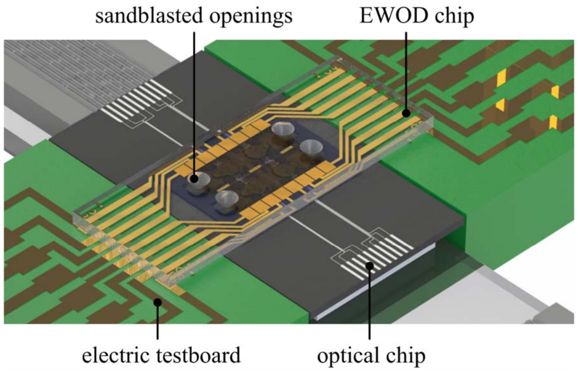

Figure 3: Rendered 3D-Model of the chip assembly.

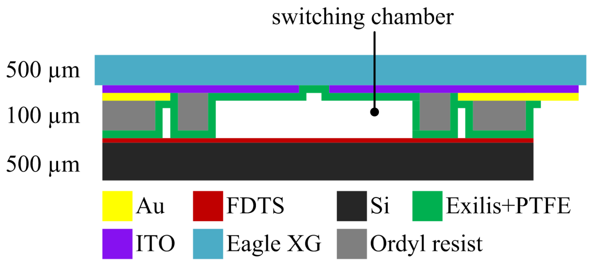

Figure 4: Schematic layer structure of the fluidic chip.

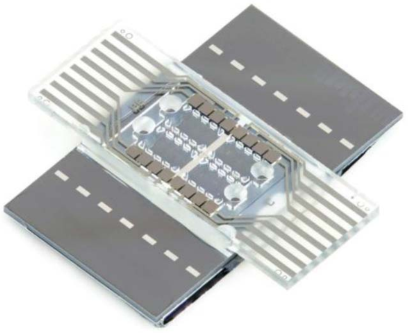

Figure 5: Photo of the assembled microfluidic chip used for the experiments.

In the last fabrication step, the EWOD cell is closed with the silicon chip containing an optical coupler (see Figure 2 and Figure 3) and sealed with a chemically stable UV-curing adhesive. The silicon chip is covered with a dewetting layer of FDTS known from the nanoimprint lithography [7]. The FDTS is deposited from vapor phase and forms a monolayer, that exerts a negligible effect on the optical performance of the adiabatic coupler.

The EWOD actuation test is carried out using a fluidic chip assembled to a silicon chip coated with FDTS without optical functionality (see Figure 5). It has the same fluidic properties as an optical chip.

EXPERIMENTAL RESULTS

Liquid actuation

The feasibility of EWOD actuation of the new liquid system is successfully realized by experiment. An AC voltage signal is used to minimize the charging and polarization effect of the dielectric. The frequency was varied between 100 Hz and 700 Hz in the experiments. Actuation with AC frequencies down to 100 Hz leads to a reduction of the energy consumption of the switching process. Identical signals but with a 180° phase shift are applied to adjacent electrodes to produce an alternating electric field vector with a constant amplitude (see the schematic graph of the signals in Figure 2). Inactive electrodes were grounded.

A sequence of droplet movement images using EG in DPS can be found in Figure 6. A rectangular electric signal with 500 Hz frequency (f) and 35 V amplitude (U_{pp}) was used. In this case the consecutive actuation of single electrodes was sufficient for the droplet movement.

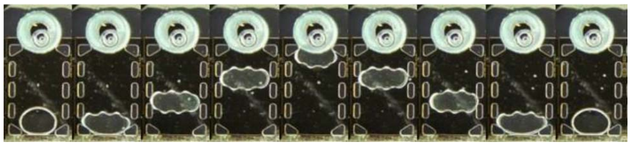

Figure 6: Captured frames of the EG droplet motion in the microfluidic optical switch with DPS as the ambient liquid.

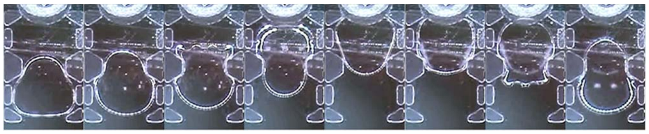

Figure 7: Captured frames of the HPC droplet motion in the microfluidic optical switch with TPS as the ambient liquid.

The video frames in Figure 7 show the actuation of HPC in TPS (U_{pp} = 35 V, f = 100 Hz) inside a cell with fluidic barriers included. The droplet motion here is enabled by turning on pairs of electrodes successively. The electric field strength between the two electrodes and the floating silicon photonic chip creates the necessary force on the droplet to move it through the stabilizing narrow section [8].

Approximately one day after actuation bubbles were visible on the FDTS surface (see Figure 10). The bubbles had no influence on the actuation and vanished after moving the droplet into the neighboring position.

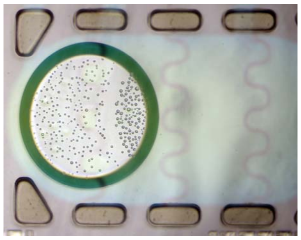

Figure 10: Bubble formation approximately one day after liquid filling.

EWOD experiments with HPC droplets in TPS were repeated successfully 30 and 60 days after filling to investigate the long term stability of the set up.

Absorption measurements

The absorption and refractive index of the presented liquids in the telecommunication wavelength range were measured in order to verify the proper optical behavior. It was found that liquids containing O-H and C-H bonds show absorption peaks in the targeted wavelength range due to the molecular vibrations of these groups. This can be avoided by deuteration of the liquids (noted with -d_x), i.e. the hydrogen atoms are exchanged by deuterium, the second isotope of hydrogen. In Figures 7, 8 and 9 absorption measurements of DPS, EG and HPC in deuterated and non-deuterated forms are shown, respectively. In HPC only the OH groups were deuterated. These measurements prove that the deuteration process leads to a significant reduction of the absorption in the targeted wavelength range.

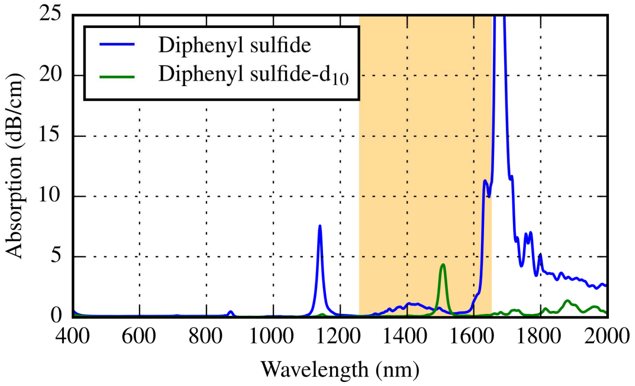

Figure 7: Absorption measurements of DPS with and without deuteration.

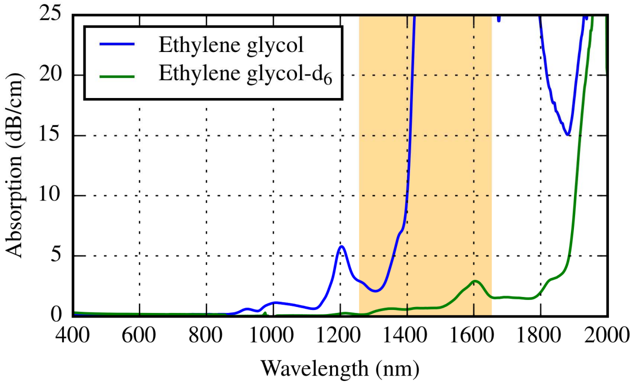

Figure 8: Absorption measurements of EG with and without deuteration.

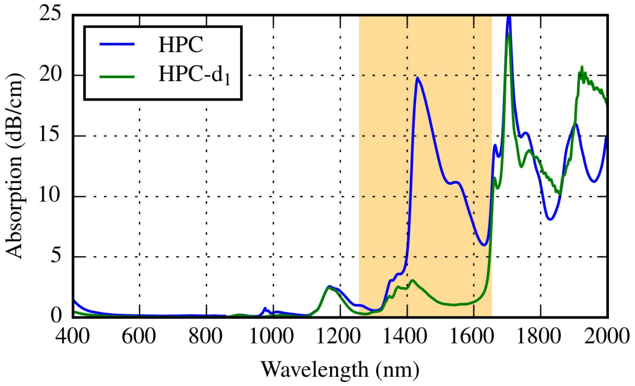

Figure 9: Absorption measurements of HPC with and without deuteration.

SUMMARY AND OUTLOOK

EWOD actuation in a microfluidic chip with two liquids for optical switching in the telecommunication wavelength range was tested successfully. The fluidic design of the microsystem enables two stable non-volatile switch positions. The required contrast in the refractive index for optical switching is achieved by diphenyl sulfide (DPS) or triphenyl sulfide (TPS) as ambient medium and ethylene glycol (EG) or hydroxyl propylene carbonate (HPC) as droplet liquid. By deuteration the absorption of DPS, EG and HPC was significantly reduced in the wavelength range between 1260 nm and 1650 nm.

It is assumed that the deuteration process only affects the absorption characteristics of the liquids and other relevant parameters relevant for EWOD actuation are unaltered. An experimental verification of this assumption is in progress. Whether the bubble formation phenomenon (Figure 10) affects the optical coupling will be analyzed in future work. Furthermore, additional testing is planned to determine long term behavior of all liquid combinations.

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