On the way to **Planar Optronic Systems**

presented by: Prof. Dr.-Ing. Ludger Overmeyer
Outline

- Introduction
- Vision of sensor concepts
- Materials
- Production methods
- Characterization
- Summary
Hypotheses

- Light will be the main future media for signal transmission.
- Measured signals will be converted into light.
- Electrical signals will be exchanged for light signals.
- A fully optical world?
- What do we need to get there?
Why optical technologies?

Assumption: Optical systems will supplement/replace electronic systems in many areas of application.
Why using photons?

- Variety of planar sensor concepts
- Low energy consumption
- High bandwidth
- Electro-magnetic compatibility
- Simple multiplexing
- High integration density on various scales
Planarity is the key to the integration and processability in parallel processes.
Why using polymers?

- High functionality; versatile material class
- Modifiable to the application
- Efficient processability, even at high throughput, e.g. reel-to-reel process
- Simple build-up of large-scale systems
- Small layer thickness = high resource efficiency
- Hybrid-systems for trans-technology matrix structures possible
Reel-to-reel production
Integration of electronics

Past

Present

Past

Present

Sony

ATI
Planar integration of optics

Waveguides

Active elements

Beam forming

Pang et al.

Sandström et al.
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PlanOS animation
What about future applications?

**Movie 3:** Application example, biomedicine technology (Lindner, 2014).

**Movie 4:** Application example, construction surveillance (Lindner, 2014).
Possible and new sensor concepts

- Interferometric sensors
- Strain detection sensors
- Temperature detection sensors
- Whispering gallery mode sensors
- Planar optical polymer foil spectrometer
Mach-Zehnder interferometric sensor

- Simulation for two bending paths
  - Cosine function
    \[ x(z) = h \cdot \left( \frac{z}{l} - \frac{\sin(\frac{2\pi z}{l})}{2\pi} \right) \]
  - Sine function
    \[ x(z) = h \cdot \sin^2 \left( \frac{\pi z}{2l} \right) \]
  - Loss_{\text{Cos}} < Loss_{\text{Sin}}

Fig. 15.1: S-bend functions for Mach-Zehnder interferometer (Hofmann, 2014).

Fig. 15.2: Transmission within S-bends (Hofmann, 2014).
Inverted rib waveguide

\( H = 500 \text{ nm} \)

Ribbon waveguide

\( H = 500 \text{ nm} \)

Hofmann, 2014

Planar integrated strain detection sensors

- Conversion of geometric strain into intensity modulation
- Micro-lenses focus beam
- Intensity dependent on elongation, i.e. distance to focus of beam

**Fig. 17.1** (top, bottom left and right): Readout strategy of the strain sensor, shown for one detection waveguide (Kelb et al., 2014).

Planar integrated strain detection sensors

- Conversion of geometric strain into wavelength modulation
- Strain detection threshold 1 ‰ with CCD spectrometer
- Sensitivity limited by dispersion of uncollimated beam

Fig. 18.1: Chromatic strain sensor with grating (Kelb, 2014).

Fig. 18.2: Experimental setup of chromatic strain sensor for proof of concept (Kelb, 2014).
Planar integrated temperature detection sensors

- Negative thermo-optic coefficient
- Positive thermal expansion
- Material characterization extremely important
- Small spectral shift (-7×10^{-3} nm K\(^{-1}\)) → Detection?

Same order of magnitude

\[
\frac{dn}{dT} = -111 \times 10^{-6} \text{ K}^{-1} \\
\alpha = 75 \times 10^{-6} \text{ K}^{-1} \\
(\text{Weber, 2003})
\]

\[
\frac{dn}{dT} = -120 \times 10^{-6} \text{ K}^{-1} \\
\alpha = 70 \times 10^{-6} \text{ K}^{-1} \\
(\text{Suhir et al., 2007})
\]

Fig. 19.1: Concept for temperature sensor based on fiber-Bragg grating (IMTEK, Freiburg).

Fig. 19.2: Simulation results in PMME according to Weber (Sherman, 2014).

Fig. 19.3: Simulation results in PMME according to Suhir et al. (Sherman, 2014).

Whispering gallery mode resonators

- Foil integrated Whispering-gallery mode sensors
- Resonant frequencies very sensitive to changes on surrounding refractive index
- Ultimate target sensitivity: single-molecule detection in liquid phase

Simulation with RSoft

- Ring-resonator: inner diameter 4.5 µm, thickness 1 µm, n=1.59
- The left waveguide is used as an excitation source: thickness 1 µm, n=1.46
- In case of resonance: light is coupled into the ring-resonator, dip in the transmission signal

Figure 20.1: The microsphere is attached to one waveguide, another waveguide detects the transmitted signal.

Figure 20.2: Build-up of the electromagnetic field in the WGM of a 1 µm thick ring resonator, \( \lambda = 1089 \) nm (Petermann, 2014).
Simulations for singlemode waveguides

Singlemode waveguide cores with either high aspect ratio or small dimensions (< 700 nm)

ZnO nanowires in substrate against mechanical strain

Fig. 21.1: Sketch of an AWG (TU Clausthal).

Fig. 21.2: Geometry (height x width) of the simulated waveguides (TU Clausthal).

n_{cladding} = 1.5

n_{core}

h

w

Fig. 21.3: Simulations performed with PhotonDesing® FIMMWAVE, red bars represent the single-mode region (TU Clausthal).

Decoupling by implementation of ZnO-nanowires

- Adding of ammonia and PEI (polyethylenimine) improved the growth of ZnO nanowires
  - Ammonia produces Zn(OH)$_2$ (s)
  - PEI inhibits the radial growth of the ZnO nanowires.

- Nanoclusters formed in growth solution can be extracted more easily

**Fig. 22.1**: SEM image of ZnO nanowires (TU Clausthal).

**Fig. 22.2**: ZnO nanowire growth principle (TU Clausthal).
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We need tailored polymers!

- **Target**
  - Development of polymers with tailored optical & thermo-mechanical properties for polymer waveguides

- **Concept**
  - Prepolymer synthesis with respect to
  - adjustable physical properties
  - use in a variety of shaping/molding techniques

- **Prepolymer**
  - adjustable viscosity ($10^{-3} – 10^{2}$ Pa•s)
  - UV/Vis curing favorable

- **Polymer**
  - adjustable refractive index ($1.39 < n < 1.65$ @ 589 nm)
  - optical damping less than 1 dB/m
  - continuous operation temperature > 100°C
Refractive index tailored hybrid polymers

- Prepolymer → MMA/PMMA/1,3-Butandioldimethacrylate (BDMA)
- Polymer → Poly(methylmethacrylate-co-1,3-butandioldimethacrylate)
- Dopant → Phenanthrene

Fig. 25.1: Viscosity adjustment with prepolymer concentration, 5 Pa·s > η > 0.15 Pa·s, @100 1/s, 60°C (IMTEK, Freiburg).

Fig. 25.2: Refractive index change with dopant concentration, 1.49 < n < 1.55, @589 nm, 20 ℃ (IMTEK, Freiburg).
Thermal properties of tailored polymers

- Glass transitions and/or decomposition reactions are monitored by Differential Scanning Calorimetry (DSC).

**PMMA**
(substrate material)

\[ T_g = 124 \, ^\circ C \text{ (20 K/min)} \]

**PMMA-2.5%SSAz**

\[ T_{g,1} = 130 \, ^\circ C \text{ (20 K/min)} \]
\[ T_{g,2} = 140 \, ^\circ C \text{ (20 K/min)} \]
\[ T_{\text{dec}} = 205 \, ^\circ C \]

**PFA-2.5%MABP**

\[ T_m = 78 \, ^\circ C \]
Molecular weight has strong influence on embedding of nanoparticles into the polymer matrix.
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Fig. 29.1: Planar optronic sensor system; highlighted waveguide (Wang, 2014).

Production concepts for integrated waveguides

- Laser processes
  - fs-laser processing
  - UV-photolithography

- Hot embossing and nano imprint

- Printing
  - Offset
  - Flexographic
  - Inkjet

- Lamination and surface coating
Direct writing of waveguides – a new approach

- Size grows with decreased repetition rate
  - Most likely due to leakage from Pulse Picker and linear absorption
- Some spots are missing

Fig. 31.1: Direct written structures in PMMA (Pätzold, 2014).

- $P = 400 \text{ mW}$
- $v_{\text{writing}} = 30 \text{ mm/s}$

$E_{\text{pulse}} = 80 \text{ nJ}$, $NA = 0.55$, stationary spots 200 µm below surface.

- $2 \times 10^7$ pulses/spot
- $2 \times 10^6$ pulses/spot
- $2 \times 10^5$ pulses/spot

- $f_{\text{rep}} = 1 \text{ MHz}$
- $f_{\text{rep}} = 100 \text{ kHz}$

- Estimated focal spot size: 150 µm


(Pätzold, 2014)
Polymer processing with fs-laser and UV-lithography

Two-Photon-Polymerization (2PP)

Microscope Projection Photolithography (MPP)

- Red LED (Long wavelength)
- UV LED
- Chromium Masks
- CCD Camera
- Objective
- Motorized translation stage XYZ
2PP vs. MPP

Fig. 33.1: Polymer waveguides on a glass substrate (Zywietz, 2014).

Fig. 33.2: Single polymer waveguide fabricated by 2PP (Zywietz, 2014).

Fig. 33.3: SEM-image of MPP generated polymer waveguides (Zywietz, 2014).

Fig. 33.4: Polymer waveguides on a highly flexible PMMA substrate (Zywietz, 2014).

Manufacturing of coupling structures and waveguides in 350 µm-thin polymer foils

Different coupling structures have been tested

Fig. 34.1: Fabricated optical waveguides through hot embossing (Rezem, 2014).

Fig. 34.2: Waveguide structures on a silicone embossing stamp (Rezem, Akin, 2014)

Fig. 34.3: Waveguide transmission losses as a function of the bend radius simulated in Zemax and RSoft (Rezem, 2014).

Fig. 34.4: Hot-embossing tool currently under development (Kelb, 2014).
Demand: Manufacture of planar waveguide network on polymer foil

Process requirements for large scale production:
- high throughput
- high resolution

Approach: Combination of two printing processes
- Flexographic printing for prestructuring of films with high throughput
- Inkjet printing for individual complement with high resolution
High throughput production of optical waveguides

- Flexographic printing machines
  - Process development in laboratory scale
  - Verification on modified industrial scale printing machine

- Inkjet printing machines

Fig. 36.1: Flexographic printing machine in laboratory scale, IGT F1 UV

Fig. 36.2: Printing machine Speedmaster SM52 (Source: Heidelberger Druckmaschinen AG).

Fig. 36.3: Pixdro LP 50 (Source: Meyer Burger)

Fig. 36.4: Dimatix DMP 2831 (Source: Dimatix)
Flexographic printing sequence:
1. Inking of anilox
2. Polymer transfer to printing plate
3. Mirror inverted reproduction on substrate

Additive manufacturing for cost and resource efficiency

Process chain from layout to printing results:

**Fig. 37.1:** Operating principle of flexographic printing (Wolfer, 2013).

**Fig. 37.2:** Process chain from layout to print results (Wolfer, 2014).
High throughput production of optical waveguides

- Printing of multimode optical waveguides

![Computed 3D model of printed waveguide](Wolfer, 2013).

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width</td>
<td>20-1,000 µm</td>
</tr>
<tr>
<td>Height</td>
<td>4-110 µm</td>
</tr>
<tr>
<td>max. Aspect ratio</td>
<td>0.5</td>
</tr>
<tr>
<td>Speed of operation</td>
<td>50-260 m²/h</td>
</tr>
<tr>
<td>Surface roughness</td>
<td>12.5 nm</td>
</tr>
</tbody>
</table>

- Waveguide setup in layers with parabolic shape

![Possible waveguide concepts by combining the core and cladding layers](Wolfer, 2014).

High throughput production of optical waveguides

- Resulting geometries and properties
  - Layer wise application (up to 50 cycles)
  - Characteristic cross section: parabolic shape

Fig. 39.1: Confocal microscopy of printed waveguide (Wolfer, 2014).

Fig. 39.2: Cross sections of printed waveguides after different amounts of printing cycles (Wolfer, 2013).

Fig. 39.3: Cross sectional polish of printed optical waveguide on PVC substrate (Wolfer, 2014).

Simulation of printed waveguides

- Multiple printing cycles lead to:
  - Larger contact angle
  - Higher waveguide geometry
  - Geometry susceptible to manipulation

- Ray tracing simulation to estimate and optimize optical attenuation
  - Ray tracing using Zemax
  - Source @ 638 nm
  - Numerical aperture 0.27
  - Contact angle variation 15-90 degree

Fig. 40.1: Optical attenuation vs. contact angle according to ray tracing simulation (Wolfer, 2014).

Fig. 40.2: Ray tracing simulation (Zemax), light intensity in dependence of contact angle and waveguide height (Wolfer, 2014).
Simulation of printed waveguides

- **Sources of roughness**
  - Substrate surface
  - Interface of core layers
  - Interface core/cladding

  - Considered in ray tracing as Gaussian scattering

- **Approach for smoother surfaces: self alignment of polymer by local variation of surface energy**
  - Decrease of surface roughness
  - Decrease of lateral undulations
  - Higher contact angle
  - Higher aspect ratio

  - Lower attenuation expected

*Fig. 41.1*: Ray tracing simulation (Zemax), roughness considered as Gaussian scattering (Wolfer, 2014).

*Fig. 41.2*: Left: Conditioned PVC substrate with distributed acrylate. Right: Confocal microscopy of self aligned polymer (acrylate)
Reactive lamination and functionalized surfaces

- Successful lamination of COC and PMMA foils using an interlayer of a sulfonazide containing polymer

- Production of nano-composites and continuous transitions from polymer to oxide with sputtering methods
  - Ta$_2$O$_5$ nano-particles produced by a gas aggregation source on a layer of ion-beam sputtered PTFE
  - The size of the nano-particles is between 16 nm and 24 nm

Fig. 42.1: Partially laminated COC and PMMA foils (Rother, 2014).

Fig. 42.2: Ion beam sputtering (Gauch, 2014).

Fig. 42.3: SEM image of Ta$_2$O$_5$ nanoparticles (Gauch, 2014).
What about active optical systems?

Fig. 43.1: Planar optronic sensor system; highlighted diodes (Wang, 2014).
Optodic bonding as bridging technology

- High success rate → 95%
- Short process time → app. 10 s
- Mechanical strength → 23 N/mm²

Fig. 44.1 (right): Schematic illustration of optode for sideway irradiation (Wang, 2014)

- Electrical conductivity
  - panacol 4732: 0.292 Ω
  - Dymax OP-29: 0.169 Ω
  - Dymax OP-29-Gel: 0.112 Ω
  - Dymax OP-24-Rev-B: 0.110 Ω
  - Delo GB368: 0.286 Ω

Fig. 44.2: Photo of realized optode. (Low Temperature Optodic Bonding for Integration of Micro Optoelectronic Components in Polymer Optronic Systems, Wang et al., SysInt 2014, accepted).
Optodic bonding as bridging technology

**Fig. 45.1:** Success rate of optodic bonded chips dependent on irradiation time, intensity of 7070 mW/cm² (Wang, 2014)

**Fig. 45.2:** Electric resistance of optodic bonded chips dependent on irradiation time, intensity of 7070 mW/cm² (Wang, 2014)

**Fig. 45.3:** Bare Laser diode CHIP-650-P5 (Wang 2013).

**Fig. 45.4:** Image from confocal microscopy (Wolfer and Wang 2013).

Thickness < 1 µm

Challenge

Optical coupling of single mode waveguide
Integration of OLEDs and OPDs into waveguide systems

- Waveguide integrated device for detection at 634 nm
  - ITO on polymer waveguide
  - Structure optimization for high responsivity

- Optical simulations of OPD/waveguide structures
  - Mode distribution
  - Waveguide losses (loss channels)
Photodetector operation parameters

**Measured @ 635 nm**

**Dark current:**
1 nA (best) = 33 nA/cm²

**Responsivity:**
320 mA/W @ -1V
63% EQE, commercial Si ~ 80%

**Bandwidth:**
1 MHz (limited by setup)
Laser-active waveguides

Fig. 48.1: Laser-active nanoparticle generation (Sajti, 2013).

Fig. 48.2: Homogenous particle embedding (Sajti, 2013).

Fig. 48.3: Laser-active polymer waveguide (Sajti, 2013).

Fig. 48.4: Flexible laser module (Kwon et al., 2008).

Fig. 48.5: Laser-active particles in colloidal (Sajti, 2013) form.

Fig. 48.6: Size distribution of laser-active particles (Sajti, 2013).

Fig. 48.7: SEM-image of Nd:KGW embedded ormosil waveguide (Sajti, 2013).

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Measurement of optical transmission properties

- Attenuation of waveguides
- Refraction index distribution
- Light dispersion in waveguides
- Coupling efficiency between interfaces

⇒ Some examples of spectral measurement equipment
Identification of length-independent attenuation

- Light sources
  - **LED**, including confocal pattern for end face characterization
  - **Diode laser** (638 nm, 140 mW)

- Numerical aperture steplessly variable within 0.1-0.5

- Aperture sizes: 1-1,000 μm

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**Fig. 51.1:** End face of printed waveguide in optical measurement setup with focused LED spot (Wolfer, 2014).

**Fig. 51.2:** Optical measurement setup (Dumke, ITA, 2014).
Ellipsometer (Sentech)
- Thickness and refractive index measurement of thin layers (up to 100 µm)
- Operating Wavelength 280 – 1700 nm

Refractive Index Profilometer (Rinck)
- Refractive index measurements of transparent materials
- Different wavelengths (405, 635, 850, and 1320 nm)
- Measurement area: 500 µm x 500 µm

**Fig. 52.1:** FTIR Ellipsometer Sentech SE 850 (Kelb, 2014).

**Fig. 52.2:** Refractive Index Profilometer (Günther, 2014).
**Fig. 53.1:** Epocore waveguides structured on a silicon wafer (Günther, 2014).

**Fig. 53.2:** Waveguide written by laser direct writing into the substrate (Günther, 2014).

- **Epocore waveguides structured on a silicon wafer**
  - Substrate: silicon
  - Core material: epocore
  - Resolution 1.25 µm/pixel

- **Profilometer specifications**
  - Refractive index resolution up to $10^{-4}$
  - Spatial resolution: 0.5 µm
  - Wavelength: 405 nm, 635 nm, 845 nm, 1320 nm
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Sensors for excellent flight performances …

Fig. 55.1: Illustration of nerve tracks on bat wing (Türk, 2014).
... and for stress and temperature surveillance

**Movie 5**: Application example, structural monitoring of wing (Lindner, 2014).

**Fig. 56.1**: Illustration of planar sensor foil on airplane wing (Türk, 2014).
Summary

- **Planar sensors** concepts for measurement of
  - Temperature
  - Strain
  - Liquid and gaseous analytes

- Development of thermo-mechanical and chemical stable as well as refractive index **tailored polymers**

- High throughput production of waveguides in **reel-to-reel process** - a combination of
  - Printing
  - Hot embossing
  - Laser processing
  - Lithography

- **Optodical bonding** as **bridging technology**

- **Equipment available for characterization of**
  - Refractive index
  - Thickness
  - Attenuation
  - Form stability
  - Glass transition temperature
The PlanOS science team (alphabetical order):

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