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Inkjet Printing of 3D Optics for Individualized Illumination Systems

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Abstract

Additive manufacturing of optical components is one of the most challenging aspects in rapid prototyping, as optics demands not only excellent surface shape and roughness parameters for the outer geometry of the printed part, but also pose stringent requirements for the homogeneity of the printed bulk material. The paper presents an approach to inkjet print optical volumes, using the specific hybrid polymer ORMOCER and an optimized, multi-layer inkjet printing process to achieve shape deviations <20 µm PV, surface roughness in the range of <50 nm and a transparency of the printed bulk volume >95 %.

Introduction

3D printing of optics still is one of the major challenges in additive manufacturing and rapid prototyping. Next to the even for illumination applications only required surface figures of shape and roughness in particular the homogeneity of the additively manufactured optical bulk volume poses demanding challenges onto the manufacturing process. For glass, being the optical standard material, additive manufacturing is still in its infancy, while for polymers several approaches such as stereo-lithography [1] and two-photon-polymerization [2,3] have been successfully investigated and are already introduced commercially. Also inkjet printing is a promising approach [4], e.g. proposed by company LuxExcel.

For inkjet printing of 3D optical bulk volumes it is required to have a sufficient optical material that can be formulated in an inkjettable way. Then, using a layer by layer printing and UV-polymerization approach, subsequently a 3D volume can be printed that contains of individual layers with a typical thickness in the micron range and layer number of $10^{3..4}$ for object heights in the millimeter range (fig. 1). The following sections will provide insights into a specific material combination as well as results for the layer-by-layer printing approach of 3D optical bulk volumes.

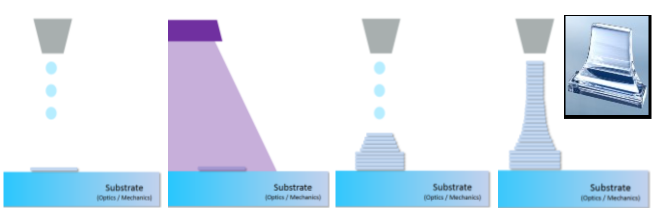

***Figure 1.** Inkjet printing process of a 3D optical volume*

ORMOCER® material for optics printing

More than 20 years ago the Fraunhofer ISC developed the ORMOCER® material based on inorganic-organic hybrid polymers. The wet-chemical linking of the characteristic structures of glass-like materials (inorganic networks) with organic structures allows for the formulation of nanocomposites (nanoscale hybrid polymers) having covalent bonds between the inorganic and organic phases. Some of the properties, in particular transparency, hardness, and thermal/chemical stability, are determined by the inorganic network. The covalent linking with an organic network enables properties such as toughness, easy processing, and additional functionalization to be realized. Via the introduction of functional groups (R), further properties such as the elasticity, surface energy, and gas permeability can be adapted to customer requirements.

The typical viscosity of standard ORMOCER® material is ca. 2 Pa·s, and thus two to three order of magnitude higher than required for inkjet printing. The standard approach to lower the viscosity by mixing the polymer with solvent is not preferred, as the solvent volume content would be in the range of ca. 70 % and needs to be evaporated after printing, resulting in long processing time and high volume shrinkage. Instead, different reactive solvents (table 1) have been investigated that remain in the polymer matrix.

Table 1: Solvent-free ORMOCER formulations for inkjet printing

	Class 1	Class 2		Class 3
Reference System	InkOrmo	ORMOCOMP +DDDMA	HC-P8	HC-P9
Network	radical	radical	radical	cationic
Curing	@N2	@N2	@N2	@air
Solvent	yes	no	no	no
Printable	yes	yes	yes	yes
λ	<400 nm	<400 nm	<400 nm	<360 nm
Optical Stability	Medium	Medium	Good	?

When formulating the inkjettable ORMOCER the resulting viscosity mainly depends on temperature and the molecule structure (internal monomer friction coefficient) and can be manipulated by changing material polarity, grade of polymerization, molecule chain length and educts. Results for two typical optical resins are:

Table 2: Realized optical resins (inks) types

Resin	Viscosity [mPas](20°C)	Refractive Index (589 nm)	Transmission >90%
A	60	1.497	485..<1000 nm
B	40	1.471	430..<1000 nm

The following figure shows the transparency of inkjet printed plan-parallel plates that have been used as a technology demonstrator for homogeneity optimization of the 3D printed bulk volume. The haze of the 1 mm thick plan-parallel plate was measured to be ca. 0.16..0.18, according to ISO-13468.

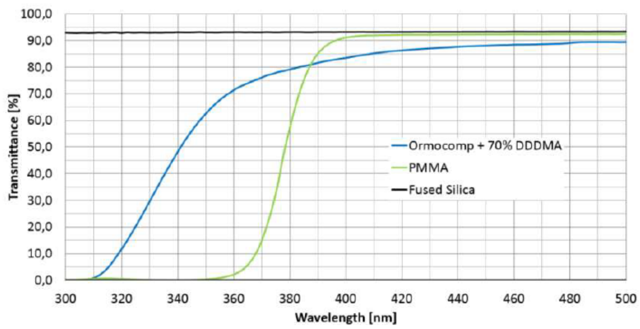

Figure 2. *Transmission curve if inkjet printed plan-parallel plate (thickness 1 mm)*

Printing process optimization

The optimization of the printing process was so far carried out without any compensation approach for systematic errors, in particular shape deviations. In general the printing work flow contains of:

- Slicing a 3D model of the bulk volume to be printed into individual images, using a typical slice thickness of ca. 1 micron,
- Calibrating the inkjet print head prior to the printing process itself,
- Doing the multilayer printing process, with a sub-sequent UV illumination of the just printed layer for polymerization of the ORMOCER,
- Finally applying a smoothing layer by printing, in particular onto the side walls of the 3D bulk volume.

Figure 3 shows typical optical volumes that have been printed that way, ranging from prismatic volumes to standard lens volumes to freeform surfaces, all in the size range of 1<>10 mm.

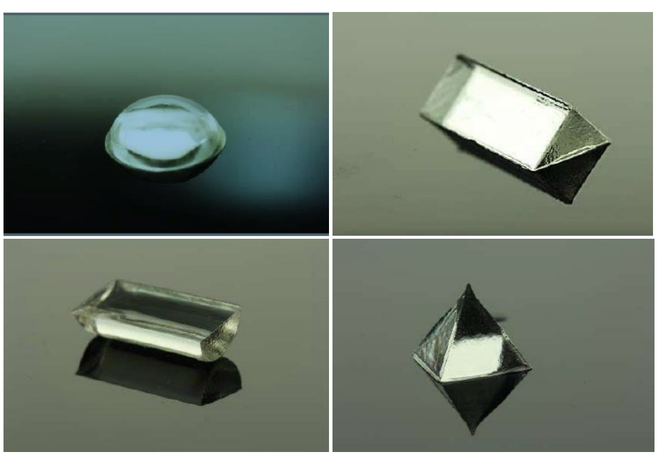

Figure 3. *Inkjet printed 3D optical volumes*

Figure 4 then shows a demonstrator geometry that was used to derive shape and roughness performance parameters. The structure itself is a simplified mockup of a typical waveguide element that is used to collimate the light of LED arrays e.g. in modern automotive headlights. It contains guiding structures with steep angle and stringent requirements onto the surface roughness also on the side faces of the light guiding structures. The structure also represents geometries that are difficult to manufacture by standard optical manufacturing technologies, such as grinding and polishing, thus also being a good example for the benefits of rapid prototyping.

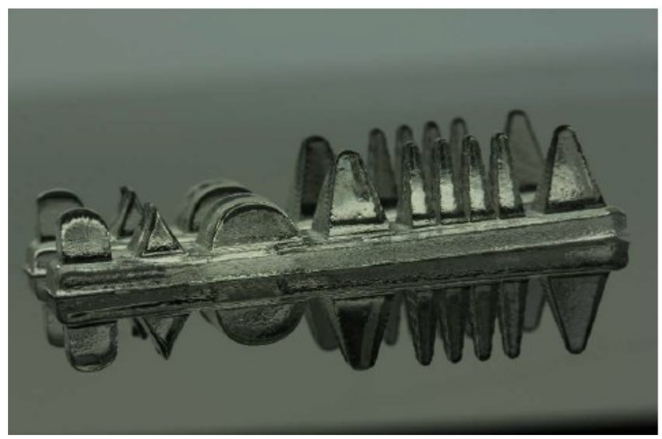

Figure 4. *Light guiding structure as primary optics for LED arrays*

Investigated printing approaches included the variation of the printing direction, a design-of-experiment approach based optimi-zation of the UV illumination of each printed layer, and a variation of the resolution and droplet size. For an optimum of 180 dpi (140 µm droplet spacing) in the printing direction, and 720 dpi (35 µm droplet spacing) perpendicular to the printing direction a typical shape deviation of

- -15 ± 60 µm (printing direction)
- - 15 ± 10 µm (⊥ printing direction)

was achieved at a resulting surface roughness of 20..50 nm rms. The height deviation of the light guiding structures was measured to be in the range of + 90 µm ± 60 µm. While for systematic errors a compensation is envisaged, the random errors make the printed bulk volumes suitable for illumination applications already.

Transmission of the printed bulk volumes was measured to by >90 % at wavelength above 400 nm. The transmission can further be enhanced by treating the printed surface via plasma etching, in order to create sub-wavelength nanoporous antireflection structures.

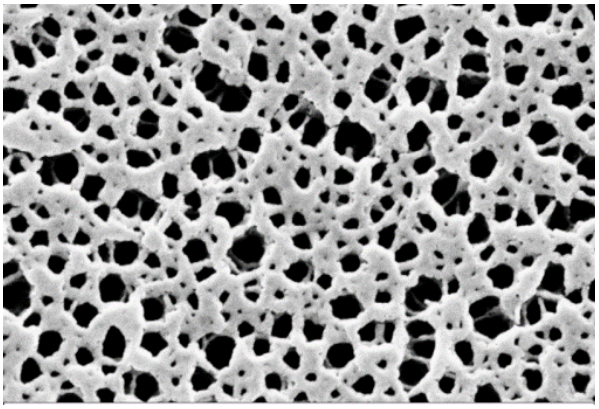

Figure 5. *Printed ORMOCER surface, plasma etched*

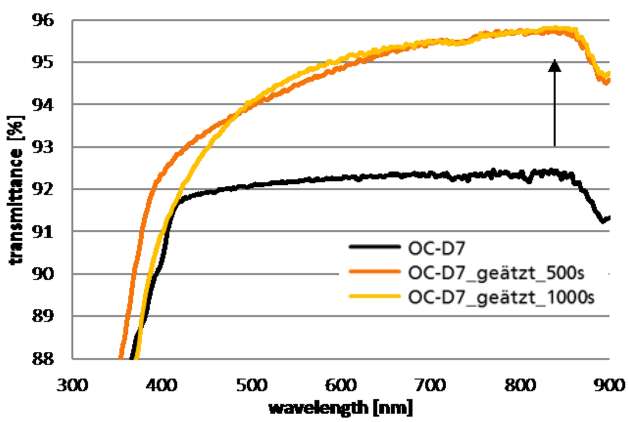

Figure 6. *Transmission enhancement by plasma etching (OC-D7 – standard surface, OC-D7-geätzt* - plasma-etched 500 s, 1000 s surface)*

Functionality integration

One of the highest most potential of inkjet printing lays, beside the printing of the 3D bulk volume of the optical material, in the further functionality integration by means of printing. It can in principle be compared to printing different colors, while here the different colors are represented by different functionalities. It was investigated that:

- Nano-particles can be mixed into the optical polymer to realize dedicated scattering layers and volumes or fluorescent quantum dots,
- “black” nanoparticles in the optical polymer lead to absorbing structures, so-called “baffles”, which are important elements in optics,
- Metallic nano-particle inks, in particular containing Ag-nanoparticles, cab be printed onto the optical surface to create surface or embedded conductive wirings or metallic reflective mirrors,
- On said wiring discrete elements such as resistors, LED or photodiodes, can be integrated by means of assembly.

Scattering structures

Figure 7 shows the scattering behavior of ORMOCER (70 µm printed layer thickness on blank glass wafer) that was mixed with ca. 10 % (weight) ZnO nanoparticles, while figure 8 demonstrates a printed haptic element for automotive applications, where the printed bulk volume is covered by a printed scattering layer to homogenize the illumination of hybrid integrated LED.

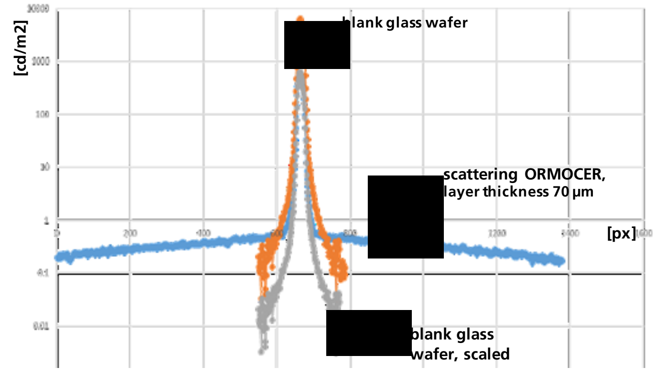

Figure 7. *Smooth scattering behavior of a 70 µm printed scattering layer*

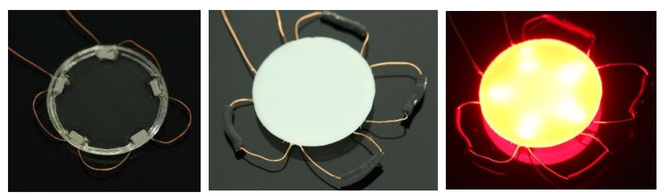

Figure 8. *Printed bulk volume with top scattering layer for LED homogenization*

Electrical wiring and Ag-mirrors

Ag-nanoparticle inks are a common technology for printing conductive tracks, this was also investigated on printed ORMOCER surfaces. Sintering of the nanoparticles is carried out by localized thermal laser treatment, photonic sintering or localized plasma sintering. By the same methodology also not only conductive tracks, but reflective silver mirrors can be realized that can further be over-printed and thus become embedded. Figure 9 shows the reflective behavior >80 % of such printed Ag-mirrors, while figure 10 shows a printed example of a mirror, embedded in a plan-parallel plate.

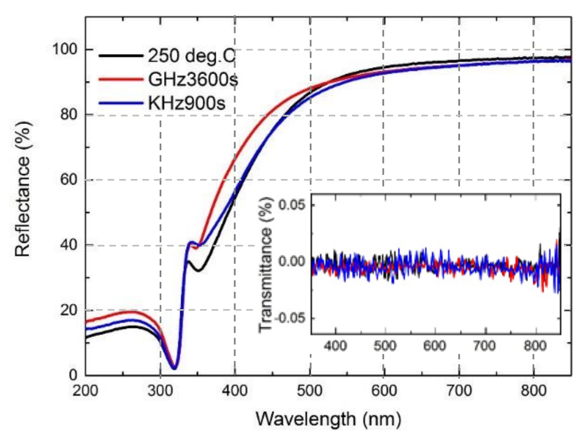

Figure 9. *Reflectivity of printed Ag-nanoparticle mirrors*

Figure 10. *Printed and embedded Ag-nanoparticle mirror*

Hybrid integrated components

Printed, conductive tracks are suitable for the hybrid integration of passive and active electro-optical elements, such as resistors, LED and photodiodes. Figure 11 shows for example a hybrid integrated low-power LED that was mounted by means of conductive adhesives on a printed ORMOCER surface.

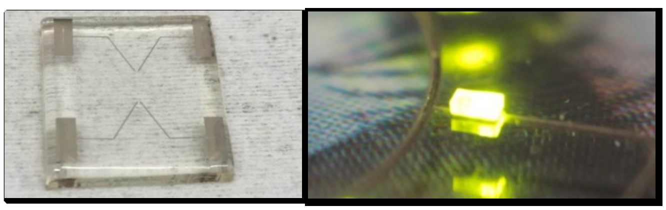

Figure 11. *Printed ORMOCER substrate with printed Ag wirings on top (left), assembled LED on the wiring (right)*

Final demonstrator

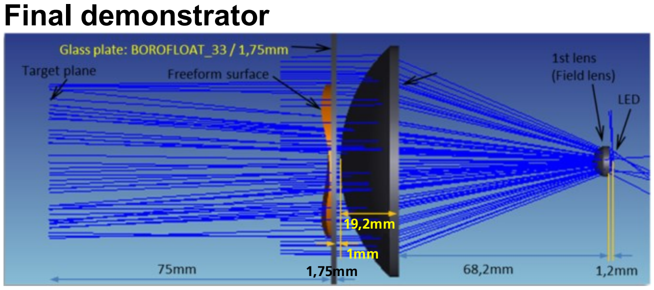

Figure 12. *LED-projection-optics + printed freeform on plane-parallel plate*

Embedding all described functionality was carried out in a free-form demonstrator that provides a patterned light distribution for collimated LED light in the far-field, e.g. for projection a logo onto a screen (figure 12). The surface shape of the optical bulk volume is a free-form that contains in a coded format the shape of the logo. Typical required surface deviations are ca. <100 µm in the center aperture of the ca. 50 mm diameter optical element. Outside of the central aperture there are conductive wirings printed and miniature LED integrated that visualize the system state (e.g. the illumination brightness or internal temperature). The demonstrator is a showcase for the vision that a standardized optical element such as a plan-parallel plate or a spherical lens can further be individualized and/or functionality enhanced by additional printing processes.

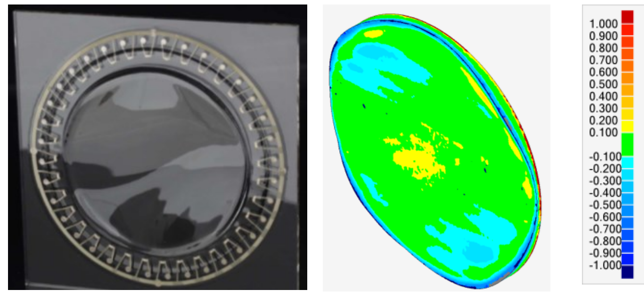

Figure 13. *Free-form with embedded wirings and LED (left), surface deviation <150 µmin 90 % of the optical aperture*

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Author Biography

Erik Beckert received a Diploma in precision engineering in 1997 and a PhD in opto-electronics system integration in 2005, both from Ilmenau Technical University, Germany. Since 2001 he is with the Fraunhofer-Institute for Applied Optics and Precision Engineering (IOF) in Jena, Germany. There he currently is a group leader for micro-assembly, system integration and quantum hardware, amongst others his research interests is also in inkjet printing of functional materials and structure