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# Optical waveguides fabricated by combination of ink-jet and flexographic printing

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## Abstract

*We present polymer optical waveguides on foils created by a combination of flexographic and ink-jet printing. While prior work focused on the creation of bare polymer tracks to guide light, this work looks into optical waveguides with a printed lower cladding layer, which makes the waveguide design independent from the optical properties of the foil substrate. First, the lower cladding is printed by flexographic printing on PMMA foil. Then, the sample is placed in an ink-jet printer, where the waveguide core is created. To control the wetting behaviour, temperature and oxygen plasma treatment are used, and continuous tracks are obtained. The waveguide functionality is demonstrated by guiding 785 nm laser light through a 20 mm long sample.*

## Introduction

Planar optronic systems are a novel concept of foil-based sensor systems that rely completely on optics[1]. By using optical sensor concepts to measure quantities like temperature[2], humidity[3, 4], or elongation[5], these systems promise to be a feasible alternative for well-established electronic systems, as they have the potential to be faster, more robust, cheaper, and lighter, than existing systems. Using foil as substrate material enables a cost-efficient fabrication of these sensor systems by using roll-to-roll compatible manufacturing processes. A key element of these systems are optical waveguides, which can be created by printing methods.

Printed optical waveguides have already been investigated by several groups[6, 7]. Generally, the researchers reported difficulties in creating structures sufficiently high to couple light into the core, which is necessary to measure the optical transmission at the end of the printed structures.

Flexographic printing allows relatively high aspect ratio structures, but it is difficult to achieve lateral feature sizes below 100 µm. Because of this, it is combined with ink-jet printing to exploit both the high speed and through-put of flexographic printing, and the higher resolution and flexibility of ink-jet printing. A lower cladding has the advantage that one becomes independent of the optical properties of the foil substrate, which before had the role of the bottom optical interface.

The optical waveguides demonstrated in this work follow previous work [8], but this is the first time that functionality of printed waveguide created by both flexographic and ink-jet printing could be demonstrated by guiding light. The waveguides are created in two process steps. First, a lower cladding layer is printed on PMMA foil by flexographic printing. Then, printing the actual waveguide core is performed via ink-jet printing. For this, two inks are investigated for ink-jet printing: An in-house developed acrylate-based monomer, and a commercially available epoxy based ink.

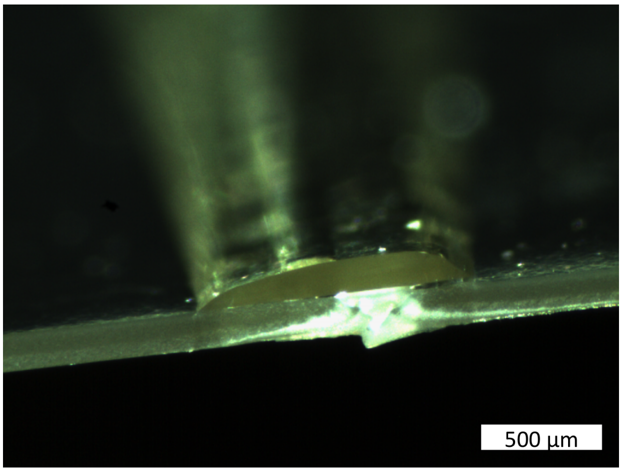


*Figure 1. Microscope image of printed optical fiber. The image shows a cross-section of the PMMA foil substrate with a printed flexographic track as lower cladding. On top of the flexographic track is a smaller, ink-jet printed waveguide core.*

| Ink Name | Manufacturer | Purpose | Refractive Index |
|---|---|---|---|
| UV-Glanzlack praegefaehig | Jaenecke-Schneemann | Cladding | 1.52 |
| InkEpo | MicroResist | Core | 1.55 |
| UGS70E | in-house | Core | 1.56 |

**Table 1: List of inks used in the presented experiments.**

## Materials and Methods

### *Inks*

A major requirement for materials used for optical waveguides is that they are optically clear. Here, this also means that there must be no particles, bubbles, and other impurities caused by printing or UV-polymerization. As the principle of an optical waveguide relies on total internal reflection, the material used for the cladding is required not only to be optically transparent, but also to have a lower refractive index than the core material. Three materials which fulfill these criteria were selected and are listed in table 1.

The ink used to create the lower cladding is a commercially available acrylate polymer ink. It has a dynamic viscosity of 200 mPa · s at room temperature and a refractive index of around 1.52 in the visible spectrum.

For ink-jet printing, two inks were available. InkEpo is a commercial product (MicroResist, Berlin)[9] based on an epoxy resin, with an volatile solvent added to reduce the viscosity to a regime compatible with ink-jet printing (12 mPa · s). The solvent has to evaporate before polymerization, which reduces the deposited volume and vastly increases the time required to fabricate a sample. The second ink is an in-house development, with a

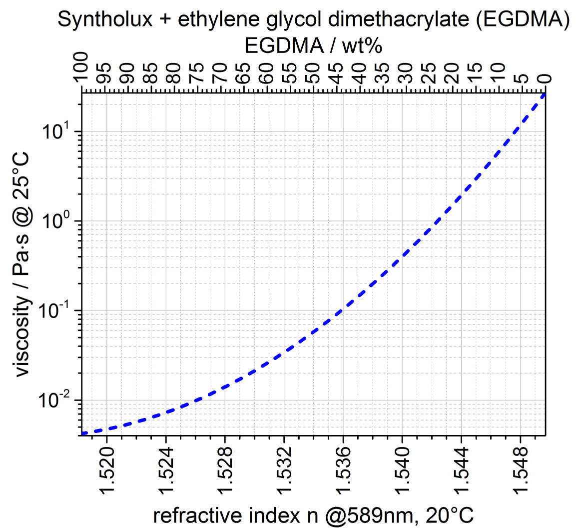


*Figure 2. Viscosity of Syntholux with EGDMA as additive. The refractive index was tuned later by adding phenantrene.*

commercially available acrylate monomer (Syntholux, Synthopol Chemie) as base material. Similarly as InkEpo, it has to match a certain viscosity to be ink-jet printable. To reach 10 mPa · s, 70 % Ethylene glycol dimethacrylate (EGDMA) are added. This material has the big advantage that it is integrated into the polymer matrix upon UV-polymerization [4], and does not need to evaporate. Therefore, the deposited volume is maintained. The effect of EGDMA on the ink viscosity and refractive index is shown in Figure 2. Additionally, phenantrene is added in the ink to increase the refractive index to 1.56, and a photo-initiator (Irgacure 184, BASF) to allow radicalic polymerization.

### *Printing Optical Waveguides*

For the flexographic printing, a Heidelberg Speedmaster 52 (Heidelberger Druckmaschinen AG) was used to print 25 consecutive layers of the "UV Glanzlack praegefaehig" on PMMA foil. The resulting tracks were 800 µm wide and 110 µm high. A detailed description of the process and parameters for printing these tracks is described in an earlier publication[8]. However, while before, the tracks were intended as the light-guiding core of an uncladded optical waveguide, here they serve as the lower cladding for an ink-jet printed waveguide core.

For this, the foils were placed in a Dimatix DMP 2831 ink-jet printer (Fujifilm Dimatix). This device allows to use a piezo-actuacted printhead with a nominal volume of 10 pl with an actuation voltage of 30 Volts to print the inks heated to 45° C to match the viscosity requirements for a reliable droplet formation. To control the wetting behaviour on the lower cladding, oxygen plasma treatment (Diener Femto O2) before the ink-jet printing and elevated substrate temperature were employed. After printing, the ink was polymerized with a Phoseon FireFly 365 nm LED light source (Phoseon Technology) .

## Characterization and Results

InkEpo was successfully used to create continuous lines with a smooth morpholgy with the substrate heated to 60° C and an oxygen plasma treatment of 60 seconds. The cross-section of this result is shown in Figure 1. Longer plasma treatment led to ink spreading, shorter plasma treatment to individual droplets. 12 layers of ink were printed. After printing, the sample was kept at 60 degrees for 1 hour to evaporate the solvent. However, it was

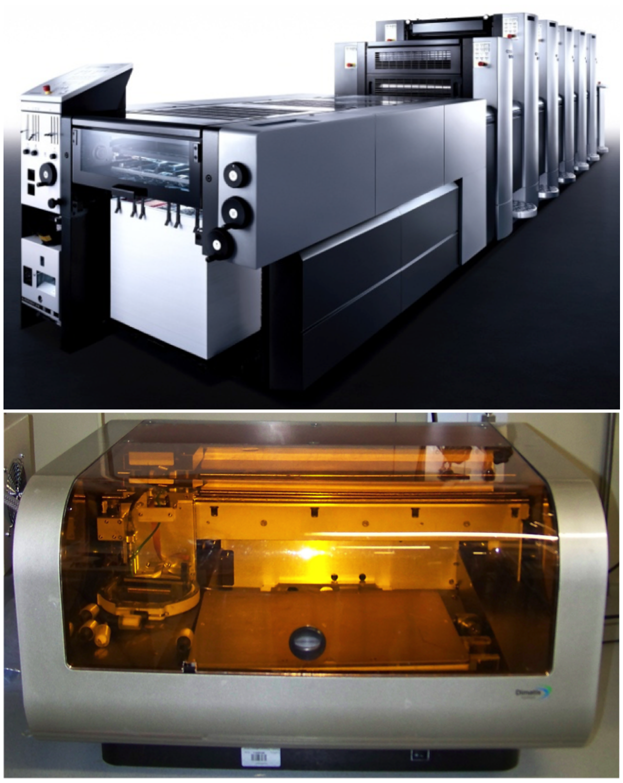

*Figure 3. Printing devices used in this research project. Top: Heidelberger Speedmaster 52. Bottom: Dimatix DMP2831.*

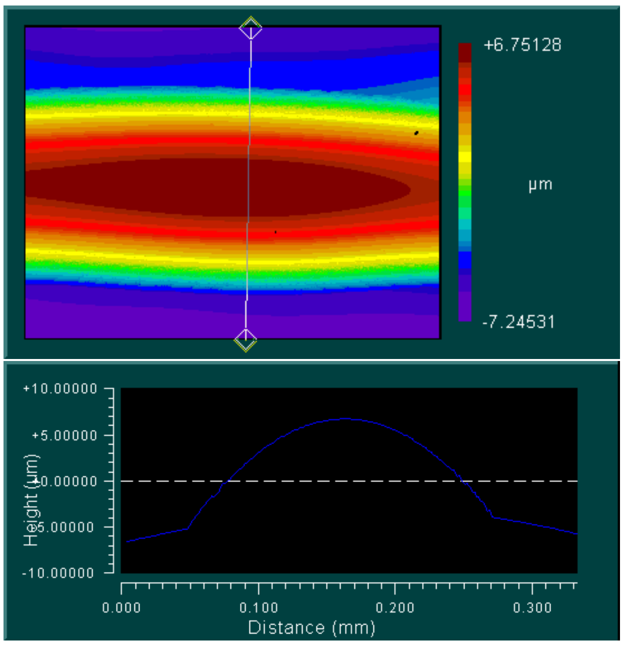


*Figure 4. Measurement plots obtained from Zygo NewView white light interferometer, showing the waveguide core on the cladding layer.*

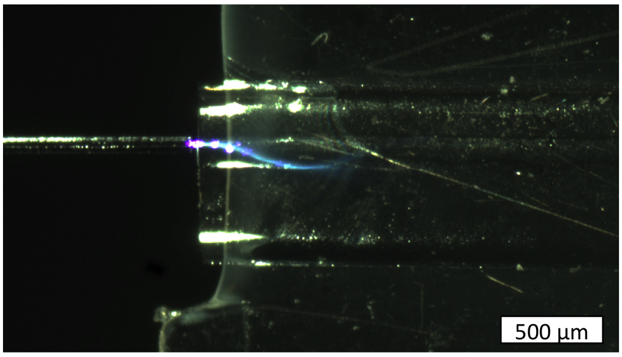


*Figure 5. View onto the waveguide facet from top through a microscope which was used to align the light source. From the left, a glass fiber carrying purple 405 nm laser light is visible. This light couples into the waveguide core and causes blue fluorescence along the beam path.*

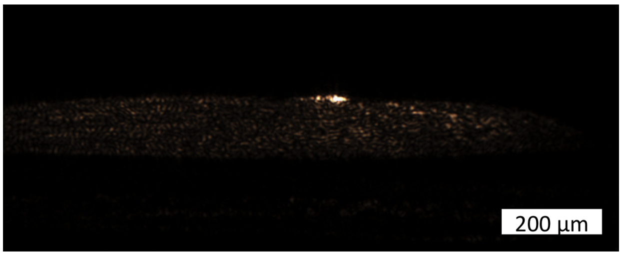


*Figure 6. Microscope image of the waveguide facet on the other side. The lower cladding is visible by stray light. The bright spot in the center is the waveguide core.*

not possible to rule out areas where the wetting was not optimal, resulting in occasional breaks of the waveguide core.

For UGS70E, it was not possible to find parameter which resulted in smooth lines. With all sets of parameters, the ink spread out on the cladding layer in an uncontrollable fashion.

### Shape of printed structures

The shape of the printed structures was characterized in a Zygo NewView100 white-light interferometer (Zygo Corporation). In the areas where the waveguide shape was smooth, the printed core fabricated by ink-jet printing is 200 um wide and about 10 um high, with variations in the range of 10% for both parameters. The measurement is shown in Figure 4.

### Optical characterization

An optical waveguide sample with a length of 20 mm was created by manual cleaving[8]. At one end of the waveguide, light was coupled by bare glass fiber facet placed under a microscope (Figure 5). First, 405 nm laser light, which causes the printed polymers to fluoresce, was used to align the glass fiber with the printed structure and visualize the beam path within the waveguide core. Then, the 405 nm laser was exchanged with a 785 nm laser with 1 mW optical power. At this wavelength, the used polymers are transparent, and the light can propagate. A CCD-Camera with microscope objective was directed at the second facet. After careful alignment, it was possible to achieve light in the waveguide core (Figure 6).

## Discussion and Outlook

Although the demonstration of the waveguide functionality was successful, it was not possible to deduct an absorption value, because of several reasons. The biggest concern is the stray light in the waveguide cladding (Figure 6), which has a significant contribution to the total measured power at the rear facet. Not

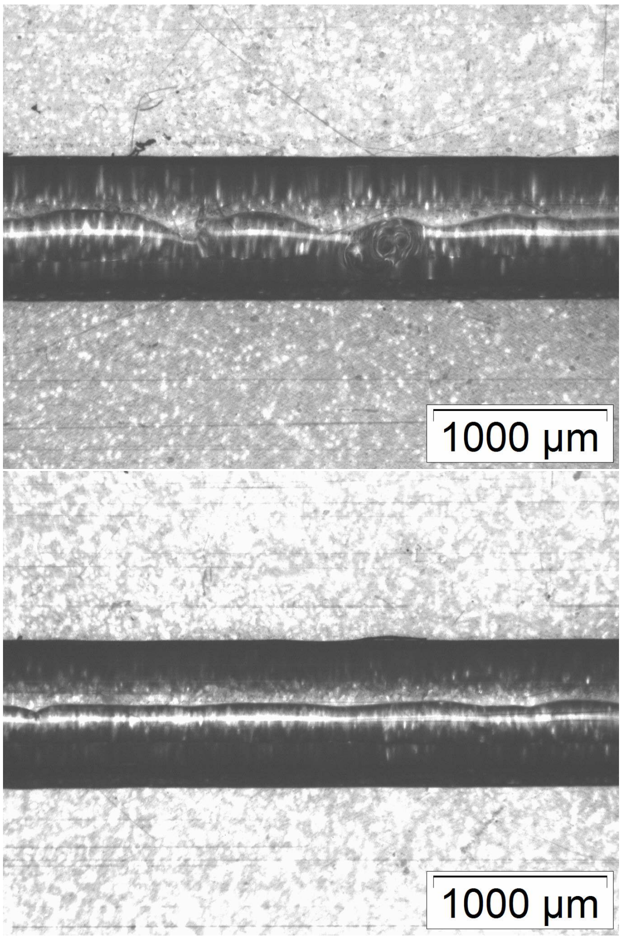


*Figure 7. Microscope images of the same line, with areas where the ink did not wet the lower cladding in a continous line, and areas where the track remained continuous.*

only does this effect make it difficult to differentiate between light in the core and light in the cladding, but it has to be investigated if the stray light is caused by bad coupling, or if the interface between waveguide core and cladding causes scattering. This scattering would be an major problem of the presented waveguide concept.

Just as reported from other researchers, control over the waveguide morphology to achieve a high aspect ratio was difficult. Figure 7 shows two sections from the same waveguide, printed with identical parameters. In some areas, the wetting is sufficient, but in other areas, the material de-wets the cladding layer and forms individual droplets. Naturally, one such hitch along a long waveguide is sufficient to disable the light guiding properties of the entire waveguide, just as it is the case for printed electronic tracks. Also even minor changes in diameter might have a significant influence on the light scattering, which is why the investigated tracks were only 20 mm long, and a value to express the attenuation per length unit cannot yet be given reliably. However, if the plasma treatment time was increased to counteract this de-wetting, then the ink began to break the line and spread out in other areas. This means that the field between too much wetting and de-wetting is very small, and therefore the process is not robust enough yet to ensure reliable processing in a mass-production application.

A possible solution for both presented problems would be to cover the entire lower cladding track, and to use the lower cladding layer as pinning edge of the printed waveguide core.

This would allow both a higher aspect ratio and a better defined morphology. The higher aspect ratio would allow more robust coupling and a better light propagation in the core.

Naturally, an optical waveguide does also require an upper cladding to protect the waveguide core. As the only requirement to this layer is an interface with the printed core, there are numerous options to achieve this, either by a locally defined deposition technique like printing, or by spin- or even spray-coating.

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## Author Biography

*Patrick Bollgruen started his studies at Uni Freiburg in 2006. Since then, he has obtained a bachelors and masters degree from the Institute of Microsystems Technology. He got involved with printing under the supervision of Dr. Patrick Smith, Dr. Dario Mager, and Prof. Jan Korvink.*