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Improving partial wetting resolution on flexible substrates for application of polymer optical waveguides

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Abstract. Considering the increasing amount of data for communication and infotainment applications, fabrication of optical networks and bus systems is a challenging task for production engineering. A two-step manufacturing process for polymer optical waveguides is presented. By improving the highly efficient flexographic printing technology by laser functionalization of the printing tool in combination with a subsequent spray application, high-quality waveguides are accomplished. By adjusting the resulting surface energy of the foil substrate in the first fabrication process, the spray application achieved high-aspect ratio waveguides with a low attenuation of 0.2 dB/cm at 850 nm. © *2017 Society of Photo-Optical Instrumentation Engineers (SPIE)* [DOI: 10.1117/1.OE.56.10.103109]

Keywords: polymer optical waveguides; partial wetting; flexographic printing; laser functionalizing.

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1 Introduction

The role of optical bus systems as the backbone of emerging sensor and infotainment networks in many areas is increasingly emphasized in recently published technology roadmaps.[1] Especially, automotive, aviation, and industrial applications benefit from high electromagnetic compatibility and low weight. In addition to these advantages, the high bandwidth efficiency ($\mathrm{Gbit/s\,mW^{-1}}$) as well as the small space requirements ($\mathrm{Gbit/s\,mm^{-2}}$) of optical connections are pointed out.

To meet the high requirements for the production of structures with optical quality, a large number of processes are part of current research and development. One category of processes for the production of light-guiding structures is photochemical structuring methods. Here, UV photolithography is a frequently used process, in which, however, limitations are shown with respect to the compatibility of the polymer substrates with the solvents used. For example, the widely used solvent PGMEA (1-methoxy-2-propyl acetate) completely dissolves the frequently used substrates of polymethyl methacrylate (PMMA). Likewise, the process technology requires complex wet-chemical steps that are difficult to stipulate with a high throughput and resource-saving production.[2] The laser direct writing by a femtosecond laser as an alternative provides a high resolution of about 5 μm. However, this method has not yet been published to be adopted on thin films.[3] At a similar high resolution, the two-photon polymerization and the microscope projection photolithography have only a small structurable area of $\sim 100\,\mu\mathrm{m} \times 100\,\mu\mathrm{m}$, which excludes large-scale applications.[4,5] More than that, a very small vertical shape tolerance of the workpieces of a few single-digit micrometers is required to focus the light energy on the surface without complex adjustment steps.

A further category of available production methods for polymer optical waveguides is the replication methods. Fabrication technologies, such as hot embossing[6] which is also suitable for the fabrication of planar polymer waveguides with Bragg gratings,[7] injection molding,[8] and UV-nanoimprinting,[9] have already been successfully used for this purpose at high throughput, but these methods require elaborate and cost-intensive tools. Especially, iteration cycles for complete shaping and damage-free demolding of the tool lead to a low variability when the layout of the optical waveguides is changed. The third process category of direct printing processes appears to be a particularly suitable alternative for keeping these manufacturing technologies in perspective.

2 Procedure

2.1 *Process Principle*

To apply a light-guiding structure to a thin film substrate by means of direct printing, only a limited number of methods are suitable. Due to the three-dimensional capability, the large range of printable materials, the high resolution, and the low susceptibility to tolerances of the workpiece, aerosol jet production is suitable. For planar as well as spatial applications, this process has the decisive disadvantage of a significant overspray occurring in the printing of transparent polymers in narrow lines (<1000-μm width). This effect limits the minimum achievable linewidth. If the substrates are previously conditioned by means of flexographic printing with a pair of lines that have a low resulting surface energy, a controlled wetting behavior can provide the subsequent deposition of polymer in the resulting space.

Figure 1 shows the flexographic printing mechanism used in this research. It is based on three cylinders that roll continuously on each other. The anilox roller provides an engraved surface and is filled with a liquid functional polymer by the use of a doctor blade. The printing form with a layout of raised structures is clamped on a second cylinder. These are wetted with the functional liquid polymer upon

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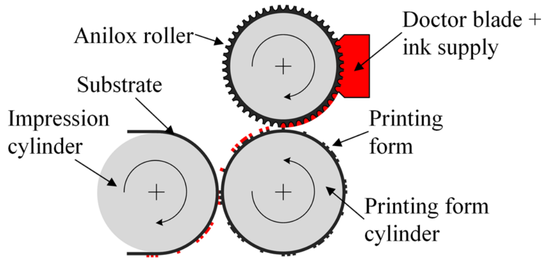

Fig. 1 Flexographic printing mechanism.

contact with the anilox roller. In the last step, the polymer is transferred to the flexible film substrate, which is tensioned on the impression cylinder. This results in a mirrored image of the layout of the printing form, which is subsequently polymerized by exposure of UV radiation.

The dewetting behavior of the conditioning lines produces a larger contact angle of the agglomerated waveguide material for the second process step as schematically shown in Fig. 2.

For an increase in the resolution and in the same time a small edge ripple of the optical waveguides, an additional modification of the flexographic printing process is necessary. A functionalization of the multiply used printing forms by means of laser processing can enable the flexographic printing process to achieve the required shape tolerances.

2.2 *Functionalizing the Flexographic Printing Form*

During the printing process, the stamp edges on the printing form may be wetted by mistake and as a result the halo effect and discontinuities result in the printed image [Fig. 3(a)]. Using a frequency-tripled UV laser (355 nm), structure sizes of 25-μm width were generated on the printing form material. When evaluating the size and shape of the structures on the surface of the printing form, the engraving of a periodic grid (grid spacing 25 to 100 μm) was performed. For the development of the process, the laser ablation rate was varied by pulse energies between 26 and 69 μJ. After structuring, the printing plate surface was coated with an epilamizing agent (Antispread E 2/50 FE 60).

By structuring the stamp edges as seen in Fig. 3(b) and an additional fluorination, the undesired wetting is prevented to achieve an increase in the conditioning line quality. As shown in Ref. 10, the combination of the laser structured surface pattern with the epilamization produces fluorine brushes. These brushes consist of polytetrafluoroethylene and thus have a lower surface energy than the photopolymer of the printing plate and limit the spreading of the functional polymer on the surface. The realized surface structure represents defects and causes pinning of the contact line.[11] These defects increase the dynamic advancing contact angle and create the described wetting behavior by combination with the fluorine brushes. This surface has a lower resulting surface energy and, therefore, causes a smaller amount of transferred polymer in the edge area between the anilox roller, the printing form, and the polymer foil substrate.

3 Results

3.1 *Printed Conditioning Lines*

The printed conditioning lines are used to produce high-quality optical waveguides. The following figure shows a comparison of the results of the aerosol jet process when using foil substrates without prior treatment and with printed conditioning lines.

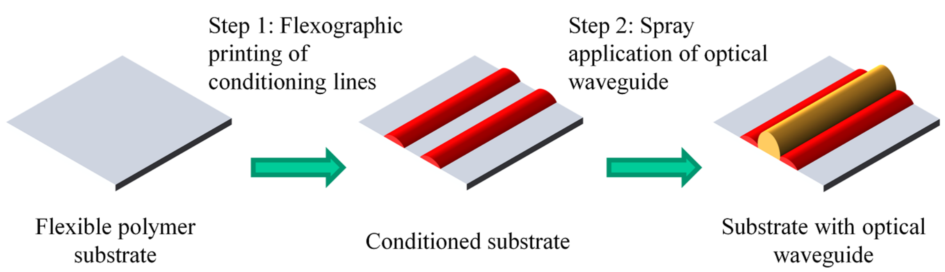

Fig. 2 Two-step process principle of printing optical waveguides.

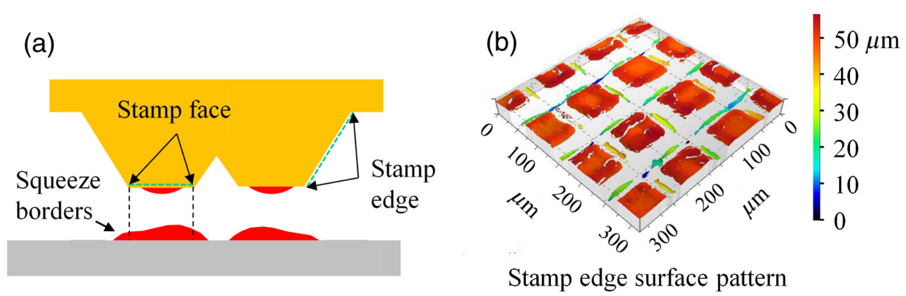

Fig. 3 (a) Shape of stamp geometry on flexographic printing form and (b) surface pattern of processed stamp edge ($E_P = 69$ μJ; $f_P = 25$ kHz).

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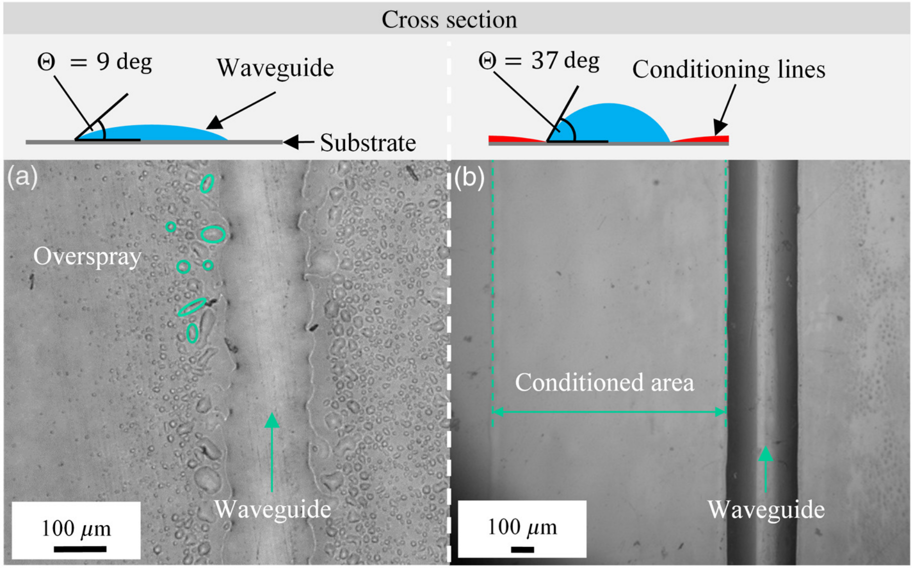

Fig. 4 Comparison of printed optical waveguides (acrylate on PMMA) (a) without conditioning lines and (b) with conditioning lines.

As shown in Fig. 4(a), the core material of the optical waveguide is applied to an untreated foil substrate. There are two effects occurring that strongly limit the usability of the printed structure as an optical waveguide. On the one hand, a significant overspray appears, which deposits fine drops on the film surface. This results in a strong edge ripple in the printed lines. If this transparent structure is used as an optical waveguide, strong attenuation effects are arising in the edge region. As a second effect, due to the good wettability of the polymer substrate, a comparatively small contact angle of 9 deg results, which is formed at the boundary of the printed core material and the substrate surface. This results in a small height of the printed optical waveguide and thus in a small usable cross section of the light-guiding structure.

In comparison, Fig. 4(b) shows the structure that is applied by the use of an aerosol jet in between the conditioning lines. These conditioning lines exhibit a low resulting surface energy of 25 mN/m and provide a substantially better wetting behavior compared to the untreated substrate at 44 mN/m. Due to these differences in surface energy, the waveguide material wets only the free space, and a significantly greater contact angle of 37 deg results in comparison to the unconditioned film, since the fluid adopts the boundary contact angle of the conditioning lines. As a result, a waveguide with a circular segment-shaped cross-section agglomerates, which has a lower optical attenuation due to a significantly lower edge ripple and a larger aspect ratio (0.2 dB/cm at 850 nm).

3.2 *Improved Resolution by Laser Functionalizing*

The implementation of the laser generated printing form structures shows the desired effect of an increase in the resolution regarding the printing results, which corresponds to an enlargement of the intermediate space between the conditioning lines (Fig. 5, enlargement of the spacing of about 30%). This results from a reduced ink transfer because of the suppressed wetting of the stamp edges. Furthermore, a reduction in edge ripple in the functionalized area can be observed (average roughness R_a up to 44% less and maximum roughness R_z up to 35%). Due to the approach of functionalizing the nonprinting area, no wear occurs during the process, since no mechanical contact takes place. Hence, an increase in the lateral resolution could be realized by means of laser beam functionalization.

An elaborate processing of the tool always means an increase in the production complexity.

Nevertheless, the laser functionalizing process has to be conducted only once. In consequence, a highly efficient production of the conditioning lines is possible. Therefore, this additional process has only a small influence on the efficiency.

3.3 *Optical Characterization*

The dimensions of the conditioned area of the waveguide and of the substrate are illustrated in a representative cross section in Fig. 6(b). The contact angle of the waveguide in the image is set to 51.8 deg with a width of 245.8 μm at a height of 59.7 μm. The optical characterization of the waveguide was performed by measuring the intensity distribution.

The intensity distribution in the waveguide is shown in Fig. 6(a). The region of the substrate appears dark in this image, since the intensity of the light coupled into this area is very small. Due to the lower refractive index of the PMMA substrate ($n = 1.490$ at 850 nm) compared to the waveguide core ($n = 1.516$ at 850 nm), the light is guided without decoupling into the surrounding cladding material. In the case of a numerical aperture ($\mathrm{NA} = 0.2$) and a spot size of 13 μm on the source side, the intensity distribution shows a typical multimodal behavior and a concentration of the highest intensity in the center of the waveguide. The measurement of the optical losses was conducted with the cutback method. An optical measuring station with integrated camera systems was used for the input and output butt-coupling situations. The positioning of the light source on the waveguide facet was realized by means of a computer-controlled parallel manipulator. During the measurement, the output power P_{L2} at the end of the waveguide with the length

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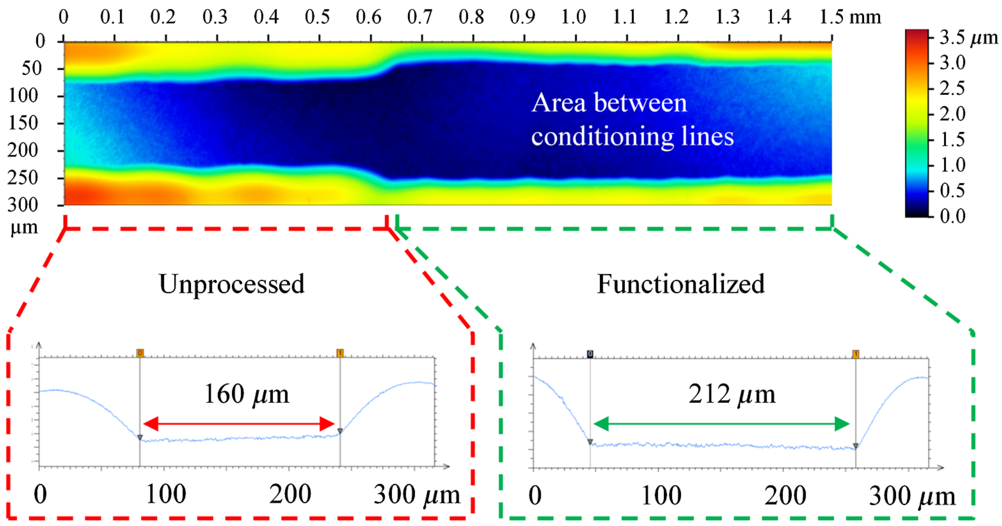

Fig. 5 Effect of printing with laser functionalized flexographic printing form.

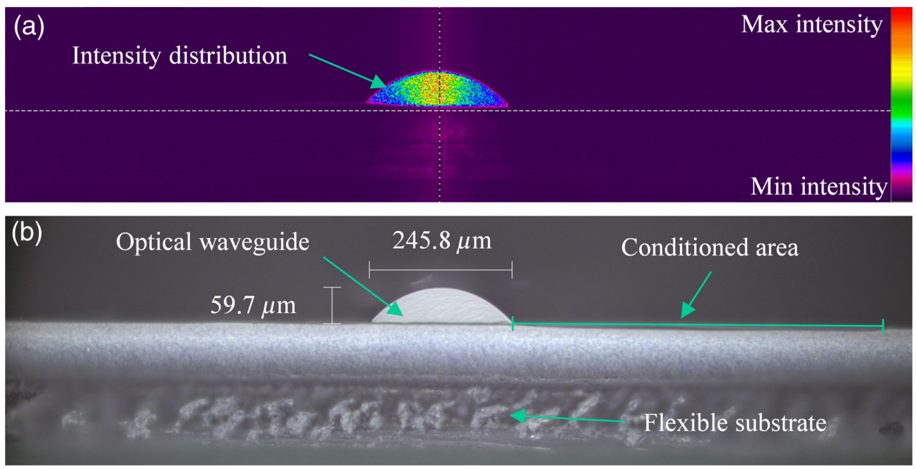

Fig. 6 (a) Intensity distribution in printed polymer optical waveguide and (b) cross section of printed polymer optical waveguide.

L_2 is measured first. After the cutback of the waveguide with a length of L_1, the power P_{L1} of the remaining waveguide is measured and the attenuation α is then calculated as follows:

$$\alpha = \frac{10}{L_2 - L_1} \cdot \log \frac{P_{L1}}{P_{L2}}. \tag{1}$$

The measurement determined an optical attenuation up to 0.2 dB/cm by the use of a laser source at 850-nm wavelength.

4 Conclusion

The results show that the two-step process is suitable for the production of high-quality optical waveguides by means of flexographic printing and a subsequent spray application. Due to the achievable optical characteristics and the efficient production at the same time, the process for the foil-based fabrication of optical networks and bus systems is a promising technology. By further increasing the resolution of the printing process by means of laser beam–functionalized printing forms, smaller waveguide cross sections up to single-mode dimensions can also be realized in the future. In addition, the full potential of the efficient process chain is given by the thermoplastic substrate, since in this way spatial optomechatronic interconnect devices can also be produced.

Disclosures

The authors declare no conflicts of interest.

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