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Conditioning of Surface Energy and Spray Application of Optical Waveguides for Integrated Intelligent Systems

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Abstract

Networks of optical waveguides allow for data transmission and sensing applications. Therefore, this technology is a key element for the integration of intelligent systems and structural health monitoring. Optical waveguides are the essential backbone to connect these structures.

The flexible and high-resolution manufacturing of waveguides, also on three-dimensional substrates, is accomplished by a combination of two printing processes. In the first step, flexible substrates are conditioned by a printing technology with an adapted flexographic printing mechanism. To produce the optical waveguide itself, the Aerosol-Jet-Printing process of liquid polymer or varnish is used on pre-conditioned areas with hydrophobic or hydrophilic behaviour. Waveguides fabricated by this two-stage process reach parabolic cross sections with a minimum width down to 10 µm. This paper shows the mechanism for the use of the processes and latest results concerning the choice of materials, which allow the operability for this kind of manufacturing. We show the adaption of the local surface energy by the printing technology to achieve a self-configuration of UV varnishes for high-resolution waveguides.

Keywords: Flexographic Printing; Aerosol Jet; Conditioning; Optical Waveguide; Surface Energy

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1. Introduction

The enormous increase of data (each year about 42 % compared to the previous year [1]), asks for new and innovative solutions of data transfer. In order to meet the increasing demands of modern communication technologies the industry necessitates optical data transfer. For long distance transmissions (>100 m), glass fiber cables are already in use. Because of their low attenuation and low susceptibility to electromagnetic fields compared to copper based solutions optics will substitute current technology in the future [1].

Regarding short distance transmissions up to 100 m the usage of polymer optical waveguides is progressively important. An example of benefit using these is the higher numerical aperture, which allows for a lower curvature radius compared to glass fibers. Nevertheless, optical short-range links are not yet competitive enough to substitute common electrical connections. The lack of suitable or robust production technologies and SMT-compatible schemes for the optical coupling between modules is one substantial obstacle. Conventional production technologies for optical circuit boards are overlay or inlay procedures where the waveguides are integrated within the electrical circuit board in a middle layer or assembled after the electrical conductors on top. [1]

However, the usage of optical waveguides on board level is mostly limited to 2D applications. Boards have to be interconnected by additional glass fiber cables or specific board connectors. As a result, the freedom of design and the potential for miniaturized and integrated components are restricted by the complex setup. Additionally, the number of optical junctions is increasing the optical loss. Therefore, 3-dimensional printing processes are investigated to enable a fully automated manufacturing of integrated optical waveguides. [2] [3]

This paper presents the latest results of printing polymer optical waveguides, by using a combination of two printing technologies, the flexographic printing and the Aerosol-Jet printing. The first step is the conditioning of the substrate materials, which is described in chapter two. Afterwards the integration of the core materials to the predefined substrate is introduced in chapter three. Chapter four highlights the benefits of the combined production process compared to current technologies.

2. Conditioning of Flexible Substrates

2.1. Functional Flexographic Printing

Flexographic printing is located as a relief printing technology where the printing form consists of a flexible polymer plate. The color transfer is accomplished by wetting the anilox through an ink supply. The next step in the process is the application of ink with the embossed structure onto the deployed substrate. This process is principally used for package printing. The functional flexographic printing is one field of activity in the special research project (PlanOS) [4]. With the possibility to achieve optical, electrical or mechanical functions, it is an innovative manufacturing process.

The incentive of the research group “Optical integrated circuit packaging for module-integrated bus systems (OPTAVER)” is the development of optical packaging in integrated circuits for optical bus systems. The printing of polymer optical waveguides is one part of this project. A novel production process to improve the optical quality, like attenuation and the integration for intelligent optical systems by realizing smaller cross sections was developed.

2.2. Printing Conditioning lines

One disadvantage of printing optical waveguides by flexographic printing devices is the low aspect ratio of light guiding structures [5]. This large difference between waveguide height and width, leads to degradation of optical attenuation due to multimode dispersion. It further complicates coupling into the waveguide because a low numerical aperture and precise alignment are required. The quality of current aerosol jet printed multimode waveguides with cross sections below 100 µm on flexible substrates does not reach the specification needed because of waviness on the surface and the boundary area. Our novel two-stage process prevents the waveguides from this quality loss. It combines the flexographic printing with the Aerosol-Jet-Printing. In the first step, the surface characteristic is adjusted selectively by printing conditioning lines on the flexible substrate. The waveguide itself is applied in the second step by Aerosol-Jet-Printing between the printed conditioning lines. These lines operate like barriers for the core material and force it to generate a smooth boundary surface.

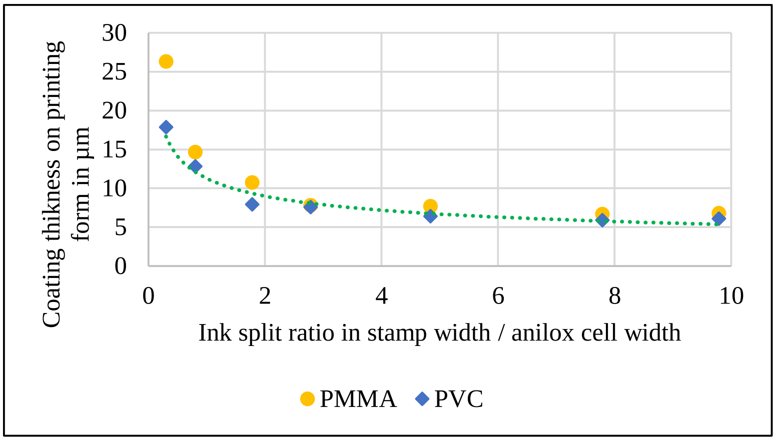

Fig. 1 Coating thickness on printing form as a function of the ink splitting ratio

The conditioning of flexible substrates for the application of polymer optical waveguides is affected by the same parameters as the conventional flexographic printing of optical waveguides. During the absorption of varnish from the anilox roller, the ratio between cell and stamp size is important. This parameter leads to an amount of varnish on the printing form, which participates in the ink splitting mechanism on the substrate. Experiments with different combinations of stamp width and anilox roller and the use of different substrates showed that the constant coating thickness on the stamp face is accomplished by using ink split ratios above two (stamp width / anilox cell width) (Fig. 1).

Constant amounts of ink allows for predicting the actual line width or distance between two lines. This value is determined by squeezing out the varnish at the edge of the stamp. To provide an intended gap size between two lines, it is necessary, to keep this parameters at a constant level. Fig. 2 principally shows the process of line enlargement.

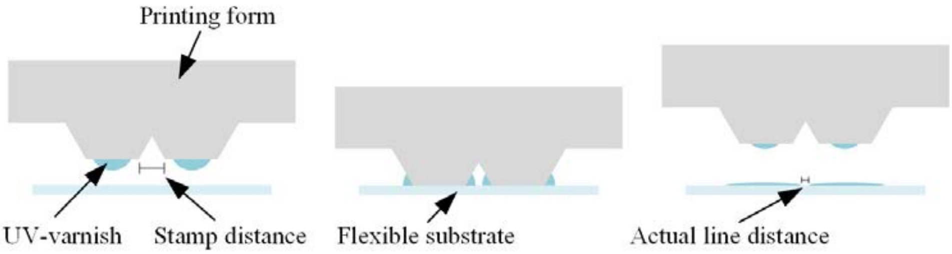

Fig. 2 Line enlargement during printing process

2.3. Surface Tension for Self-Configuration

Printed conditioning lines cause a 3-dimensional self-assembly on the varnish, which is sprayed above [6]. The fluid tends to dewet the conditioned areas because of the lower surface energy compared to the substrate. These areas act as regional barriers. The process of self-assembly is shown in Fig. 3 (left hand side). This image shows a sequence of six pictures taken in about five minutes. The progress from Image “a” to “f” illustrates the UV-varnish retracting from the conditioning lines and creating optical waveguides by self-assembly.

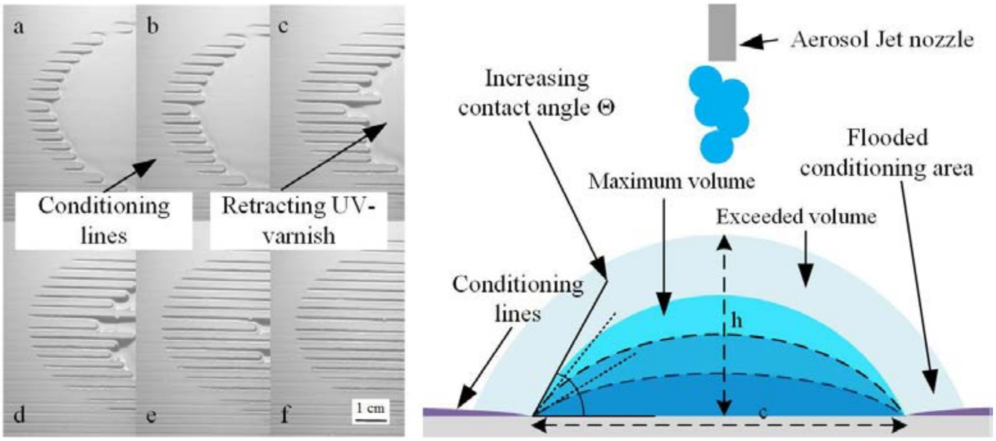

Fig. 3 Left: Three dimensional self-assembly; Right: Amassed varnish between conditioning lines

The amount of amassed material between these barriers depends on the interaction at the surface. After the completion of the dewetting process from the conditioned areas, the waveguide material only affects the substrate between it. The contact angle equals the contact angle the varnish would create on the coated areas with a lower surface energy. The area between the barriers is filled up with varnish as far as the maximum contact angle is not exceeded (Fig. 3 right hand side). After the maximum aspect ratio is reached, the shape is no longer affected by the different surface energies and will flood the area inordinate. To comply with these limits it is necessary to calculate the maximum aspect ratio reachable with the barriers. Each printed line, up to a certain size, creates a segment of a circle. As the maximum contact angle is common and the distance between the lines is defined as chord length, the aspect ratio τ can be determined. It is defined as the chord length c divided by the sagittal length h, using Equation (1).

$$\tau = \frac{c}{h} = \frac{c}{2} * \tan\left(\frac{\theta}{2}\right) \tag{1}$$

Fig. 4 shows a function of the possible aspect ratio depending on the chosen conditioning material. The current experimental results refer to an UV-varnish from Jänecke+Schneemann (J+S) on conditioned areas printed with a silicone containing varnish from ACTEGA. With this material combination, waveguides with an aspect ratio of 0.29 can be produced. The subsequent process will use this information to determine the required volume flow rate.

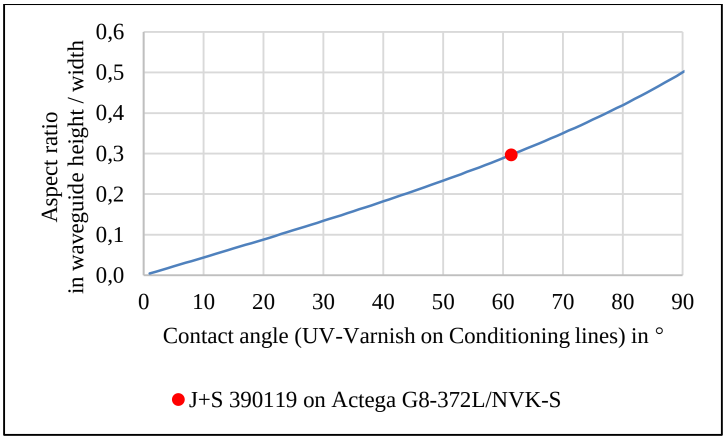

Fig. 4 Possible aspect ratio as a function of the used contact angle

Figure 5 shows an image of recent results made for optical waveguide between the conditioning lines. It was measured with a confocal microscope and demonstrates the dewetting functionality in consequence of the lower surface energy and the higher contact angle on the conditioning varnish. The waveguide applied between the conditioned areas creates a smooth surface and constant dimensions over the entire length. With the downstream Aerosol-Jet-Printing process, it can reach the expected contact angle.

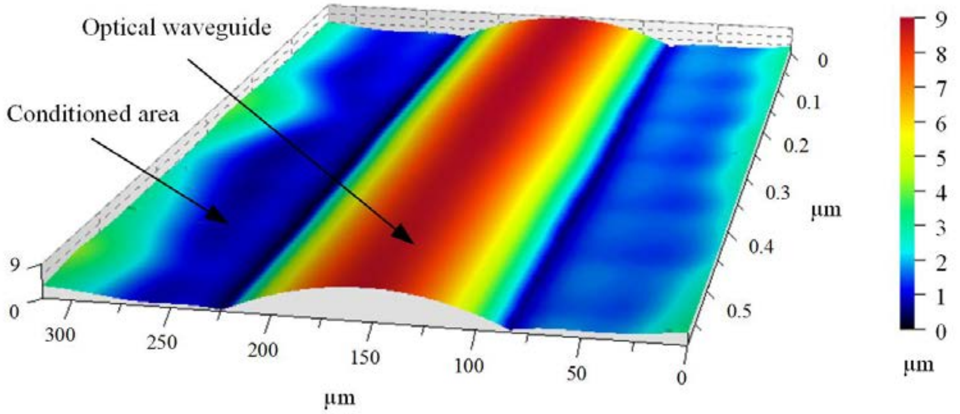

Fig. 5 Printed Conditioning lines with applied core material in between

3. Aerosol Jet Printing

3.1. General setup and printing process

The Aerosol-Jet-Printing technology offers the opportunity to print various liquid materials (inks) on almost any substrate material with an offset of up to ten millimeters. There are some restrictions regarding the ink:

1) Viscosity:	1.0 – 1000 cP
2) Shear behaviour:	shear thinning or Newtonian preferred; shear thickening is unacceptable
3) Particles:	Size: 300 – 500 nm maximum; < 200 nm preferred Solids content: 5 – 70 wt %

Multiple solid components, if used (e.g. silver and glass frit) should be equally dispersed throughout ink

By heating the polymer inks 1) can be achieved in most cases, the other points can be neglected while using liquid polymers. For transferring the ink into an aerosol, there are two ways of atomization. The first way is to use an ultrasonic atomizer where the liquid is nebulized by ultrasonic forces (Fig.6 right hand side). However, as only materials with a very low viscosity (<10 cP) can be atomized this way. This was not possible for polymer inks, even after preheating. [3] [7]

Using pneumatic atomization (Fig. 6, left hand side) the ink inside the beaker (5) is nebulized by a carrier gas stream (in most cases nitrogen) that is called atomizer gas (1). For preheating the inks, to lower their viscosity, there is a heating sleeve (6) surrounding the beaker. The aerosol is transported to the virtual impactor (3). Here a second gas stream called exhaust gas (2) with a negative pressure filters out the particles of smaller size. The bigger droplets simply fall down inside the virtual impactor because of gravity. Finally, the homogeneous aerosol reaches the nozzle (8) where a third gas stream the sheath gas (4) surrounds the aerosol for focusing it to a defined beam.

The Aerosol-Jet process itself is a continuous process, so once started the aerosol is produced until the machine is turned off again. To create different structures there is a shutter (7) which interrupts the beam for a short time. For manipulating the different substrates in even 3-dimensional domain, the machine table (9) can turn in each spatial direction. [3] [7]

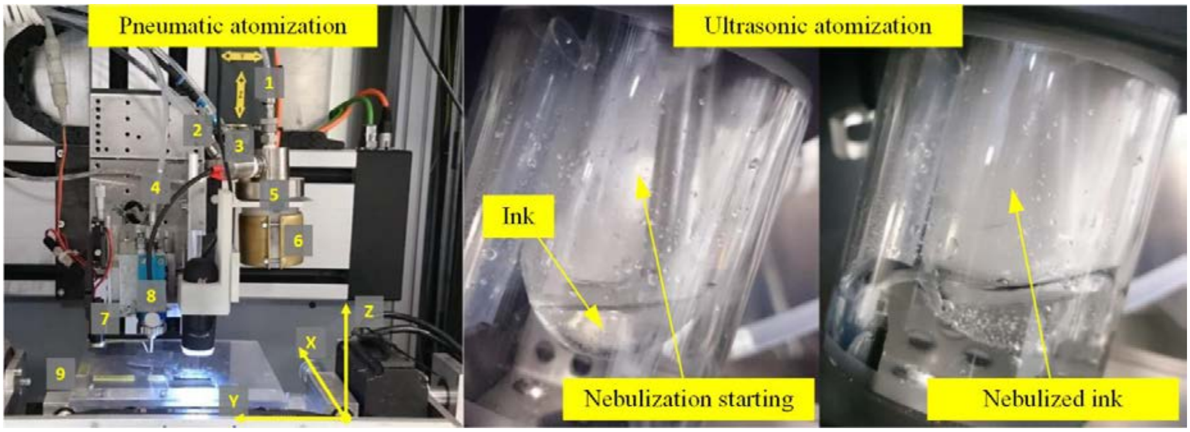

Fig. 6 Left: Pneumatic atomization; Right: Ultrasonic atomization

3.2. Material research

Different UV-curing epoxy resins were tested regarding their printing characteristics on Polymethylmethacrylate (PMMA)-foils: (1 = best results; 4 = worst results)

1) UV-varnish	(J+S)
2) EpoCore	(micro resist technology)
3) InkOrmo	(micro resist technology)
4) Loctite	(Henkel)

The main problem the Loctite resin shows is the fast and strong hardening due to the UV proportion of solar radiation. This leads to a processing window of <45 min from filling in the resin, until the tip is fully clogged. The cleaning process itself lasts about one hour until all parts are free of resin, so amber light processing is necessary here. Another problem was the building of droplets, which lead to a very unsteady waveguide structure (Fig. 7). A quiet similar behavior can be observed with the InkOrmo resin. The process window is a little bit higher (about 60 min), so processing with amber light is proposed. The waveguide also formed unsteady shapes (Fig. 7). EpoCore showed good results concerning the process window, which was over 48 hours. The printed lines had almost straight edges (Fig. 7). With $R_z = 0.7$ µm and $R_a = 0.1$ µm it features a good surface roughness as well.

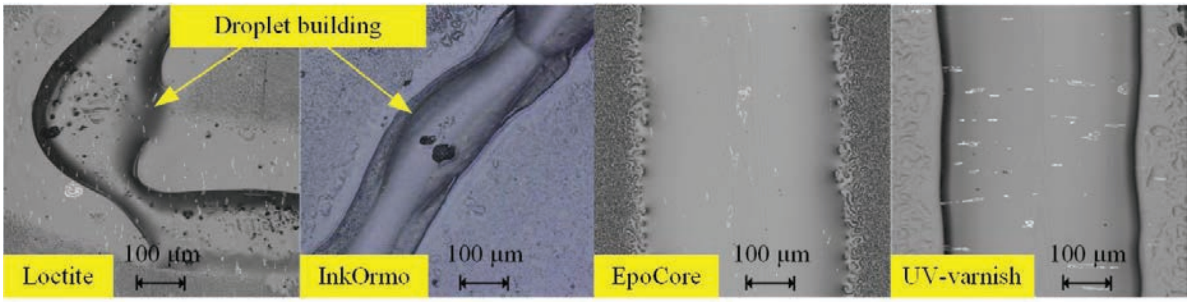

Fig. 7 Printed waveguides using different liquid UV-curing polymers

The best results were observed with the UV-varnish, which was also the cheapest material tested (100-times cheaper than EpoCore). No processing window could be asserted, even after weeks the varnish had the same characteristics as at the beginning of the tests. With $R_z = 0.8$ µm and $R_a = 0.1$ µm the surface roughness was also in a good range for optical use (Fig. 7).

3.3. Printing between the conditioned areas

After the first material tests, UV-varnish was printed between the conditioned areas (Fig. 8). The left picture shows the top view of the printed waveguide. The conditioned lines width is about 500 µm the distance between them is 200 µm. The proposed effect, that the low surface energy of the lines builds a barrier for the core material can be observed, especially on the right hand side of Fig. 8. There a crosscut through the structure was made using a laser scan microscope. The core height is about eight µm the conditioned lines are about five µm.

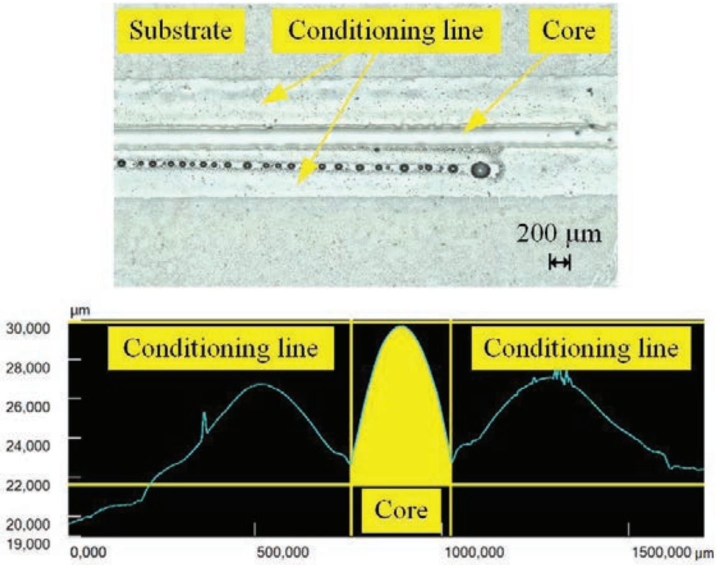

Fig. 8 Top: Top view of UV-varnish printed between conditioned lines; Bottom: Crosscut through the structure

4. Benefits of the Optaver Process

In comparison to current production processes for optical waveguides, the “Optaver” process uses the self-assembly effect of materials in fluid and solid phases with different surface energies. By using this technology it is possible to produce multiple optical waveguides with one individual operation on the preconditioned substrate. The surface and shape of the waveguides also have a higher optical quality compared to structures printed by the Aerosol Jet without preconditioned substrates. Advantages over direct flexographic printing of optical waveguides itself are a higher aspect ratio and the possibility to print on three-dimensional parts.

5. Summary and Outlook

This paper describes the conditioning of PMMA-foils by using a flexographic printing machine. The two lines build up a barrier for the core material, which is printed between them in the second process step of Aerosol-Jet printing. The effect of the self-assembly because of the conditioning lines could be verified. The next steps are to archive higher core structures by printing multiple lines on top of each other with and without curing them before printing the next line. This will be done until the maximum aspect ratio is reached. Furthermore, a cladding material has to be identified meeting the requirements concerning the refractive index and surface tension. To improve the surface quality a preparation of the printing form on which the wetting with UV-varnish is regulated could generate even better results compared to current.

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