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The future of short-range high-speed data transmission: printed polymer optical waveguides (POW) innovation, fabrication, and challenges

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ABSTRACT

One of today's megatrends in the industrial environment is additive manufacturing. Faster prototyping, customized products like hearing devices, integrated functions like heatsinks and many other opportunities are offered by this technological development. The opportunity of using different materials and build up 3-D structures is virtually infinite.

Another one is the digitalization of almost any product to build up a smart world. This trend leads to a tremendously rising amount of data to be transferred from one place to another. If a wireless transmission is not possible and if the distance is over 100 m glass fiber is the fastest and most secure way for these requirements. In case of most short-range applications up to 100 m primary copper cables or circuit paths are in use because the electrical data transfer is well known. The limited bandwidth of copper asks for new inventions to meet the demands of tomorrow. Regarding both megatrends, the solution for this upcoming bottleneck could be 3-D printed photonic packages.

This paper shows a new and innovative way for the customized fabricating of short-range data transmission networks. By Aerosol Jet Printing (AJP) the so called polymer optical waveguides (POW), it is possible to build up 3-D printed light guiding structures with low attenuation on almost any three-dimensional surface. The main advantages of the here presented research are high flexibility, low weight and low costs. After three years of intensive studies the most important key facts (machine settings, geometry, performance) are summarized in this publication.

Keywords: additive, manufacturing, polymer, optic, waveguide, aerosol, printing, digitalization.

1. INNOVATION

Additive manufacturing (AM) opens up a whole new world of possible applications (see Figure 1). Researchers, engineers and designer have to open up their minds to break out of conventional ways of thinking when producing parts. It is no longer necessary, starting from a molding, to select the particular subtractive manufacturing process with which the desired shape can be achieved. Rather the molded part itself can now be generated and, moreover, not only functionalized on its surface but also in the interior of the component. This makes it possible to produce geometries which can only be fabricated by subtractive methods under difficult conditions or not at all. [1]

The range of materials available for the AM is also very broad. Not only metals and polymers can be processed, but also ceramic materials and rare earths. For the purpose of electrical functionalization, silver pastes or inks are normally used, with copper powders and inks currently on the rise [2, 3]. Polymers are mainly used for the production of substrates, but it is also possible to use transparent polymers as light guiding structures.

In this paper, the production of so-called polymer optical waveguides (POW) in the OPTAVER process (Optical integrated circuit packaging for module-integrated bus systems) will be presented and their potential for data transmission of the future assessed. In addition to the OPTAVER process, there are currently several other approaches for the production of POW.

Flexographic Printing represents another direct printing process. Here, UV-curable polymers are applied layer by layer onto film substrate and cured sequentially. In each case, boundary layers are formed between the individual layers, which

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can contribute to a reduction in the optical signal transmission quality. Compared to the Aerosol Jet printing there is also the disadvantage of the lack of 3-D capability. [4]

In the Mosquito method, core material is injected into cladding material applied over a large area using a thin dispensing needle. Due to the molecular forces acting in the liquid phase, a largely round core structure is formed within the cladding material. However, this method is also limited to two-dimensional space. [5]

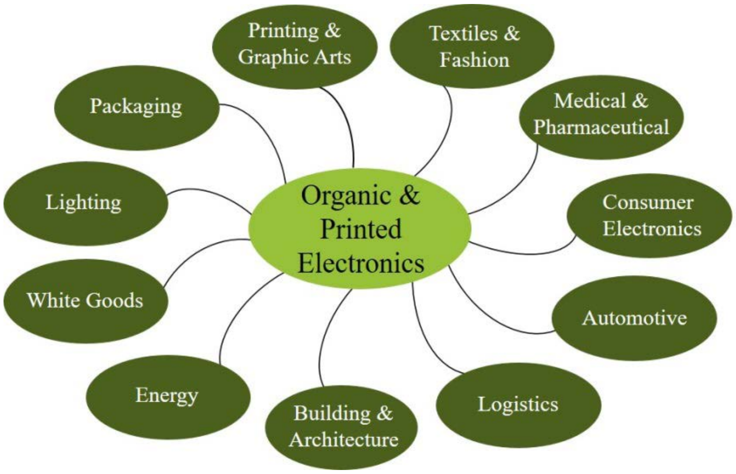

Figure 1. Overview of possible new applications based on organic & printed electronics. [1]

2. FABRICATION

The process chain for the fabrication of polymeric optical waveguides is shown in Figure 2. The extruded PMMA film is conditioned by Flexographic Printing. The conditioning is essential to force the later on printed core material to build up a defined contact angle leading to a semicircular structure of the core. The interaction between the surface energy of the conditioning (which should be low), the surface tension of the substrate (need to be higher) and the surface tension of the liquid core material defines that angle, which is 61.4 ° with the material combination used at the moment. [6]

Functional ink is applied over several rolls from the printing form to the PMMA film in the desired layout. When passing over the foil, about five micrometer high conditioning lines are produced with adjustable spaces and widths, which are UV-cured in the same machine directly in the following step. So far the best results have been provided by the lines with a distance of 250 µm to 1000 µm. On the one hand for these distances the quality of the conditioning is high regarding their edges (less than 20 µm deviation in parallelism and straightness) on the other hand the following step of AJP works best because it is possible that even the overspray of the process beam is inside these lines. This means that the whole material output of the machine, which is normally calculated in the first place, is not flooding the conditioning by any means and a maximum contact angle can be achieved. [6]

This process step is crucial for the quality of the subsequently produced optical waveguide. If the Flexographic printed lines have too large geometric deviations (<10 µm), this has a direct negative effect on the performance of the optical waveguide, since the bottom of the core represents the negative of the area between the two conditioning lines. [7]

Aerosol Jet Printing of liquid polymer between the conditioning for producing the waveguides core is the next step of production. Therefore, the varnish is transferred into fine mist with particle sizes between one and five microns by pneumatic atomization using nitrogen as carrier gas. By separating smaller droplets with a diameter up to two microns by negative pressure in the virtual impactor, a homogeneous mist is generated which is focused to a beam inside the nozzle using nitrogen. The state of the art printing parameters for processing Jaenecke + Schneemann (J+S) 390119 clear varnish are illustrated in Table 1. The core is also UV-cured. [8]

As the printing of the cladding material on top of the core is still a challenging task, this point is discussed in the following chapter. An additional UV-curing step has to be made before preparation. The end face preparation is done using a very simple method described by Wolfer et al. [9]. The waveguides are cracked manually leading to the smooth structure of the fractured face, which can be seen in Figure 3. Using this technique, no further end of face preparation is needed and the waveguide can directly be used to be integrated into an optical network.

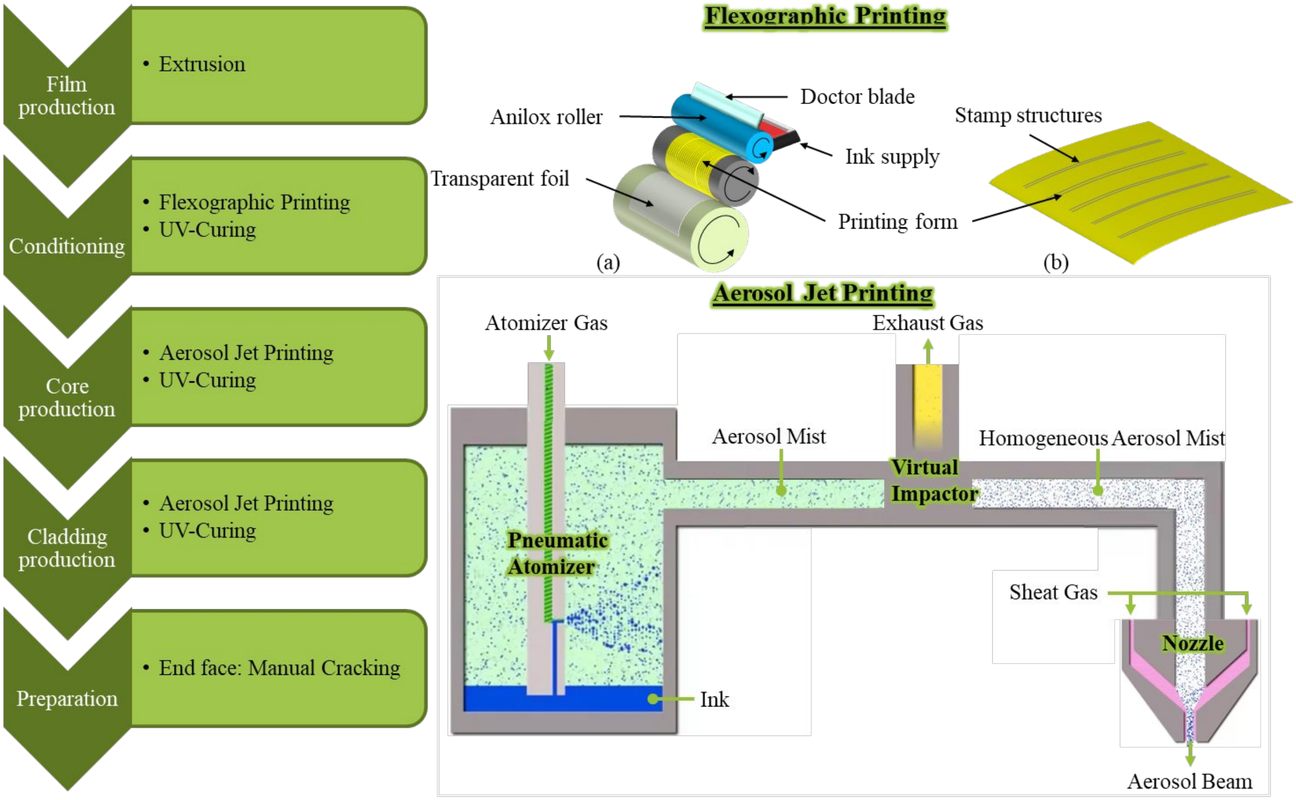

Figure 2. Process chain for manufacturing of POW by the OPTAVER process with its two main printing technologies, Aerosol Jet and Flexographic Printing [6, 7]

The OPTAVER process for producing polymer optical waveguides offers some major advantages compared to most state of the art methods of manufacturing (see [8]). The 3-D capability is one of the most interesting points for future applications when thinking of curved surfaces like the door of a car or the back of an interior panel in an airplane. These will be typical applications where polymer optical waveguides might be used in the future. Another fact is the environmental sustainability compared to the dry etching or removal of photoresist process steps where toxic chemicals are in use.

Table 1: Printing parameters used to manufacture polymer optical waveguides by Aerosol Jet Printing.

Parameter	Value	Parameter	Value
Atomizer gas	800 sccm	Distance nozzle to substrate	10 mm
Exhaust gas	740 sccm	Nozzle diameter	300 µm
Sheat gas	80 sccm	Number of crossings/layers	10
Process gas	nitrogen	Temperature varnish	40°C
Velocity	500 mm/min	Distance between conditioning	350 µm

In Figure 3 a SEM image of a typical printed polymer optical waveguide can be seen. Microscopic measurements of the surface of the printed core showed that R_a is up to 30 nm. This is the case because the printed material is still liquid when printed on the film and so the surface tension forces it to build up the shape of a circular segment with a defined contact angle. If no environmental impacts interact with the surface (which would be the case in clean room using vacuum), the surface would only show a fraction of measured values of roughness.

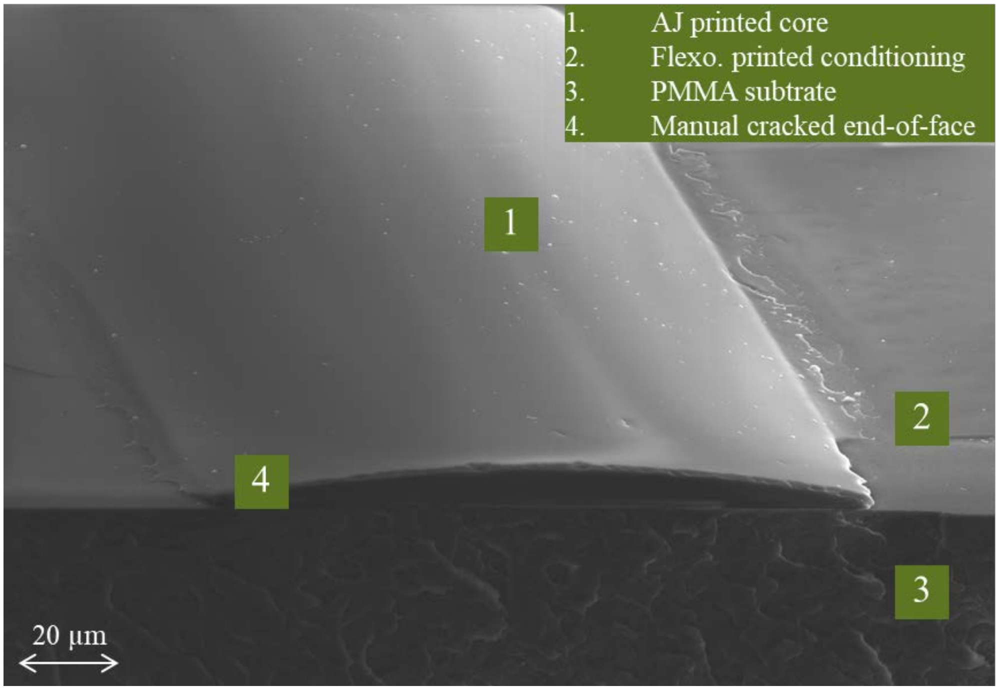

Figure 3. SEM image of a printed polymer optical waveguide.

Also a novel direct core-to-core coupling concept the so called Asymmetric Optical Bus Coupler (AOBC) has been established (see Figure 4). The coupling is based on physical contact between a curved and a planar waveguide. Depending on the respective contact pressure and the radius of the curved waveguide piece, contact areas of different sizes are formed. In general, it can be said that the larger they are, the higher is the transmission rate. Thus, signals or data from one of the two coupling partners can be transmitted to the other, wherein the transmission rate of the bent waveguide to the planar at a bending radius of five mm is 0.37 and from the planar to the bent is 0.01. Because of the bending, an asymmetric coupling (depending on the direction) is achieved. Hence, after a junction enough power is left in the bus waveguide for further coupling. This allows for bidirectional coupling of multimode waveguides on board and module level without interrupting the two coupling partners. [10]

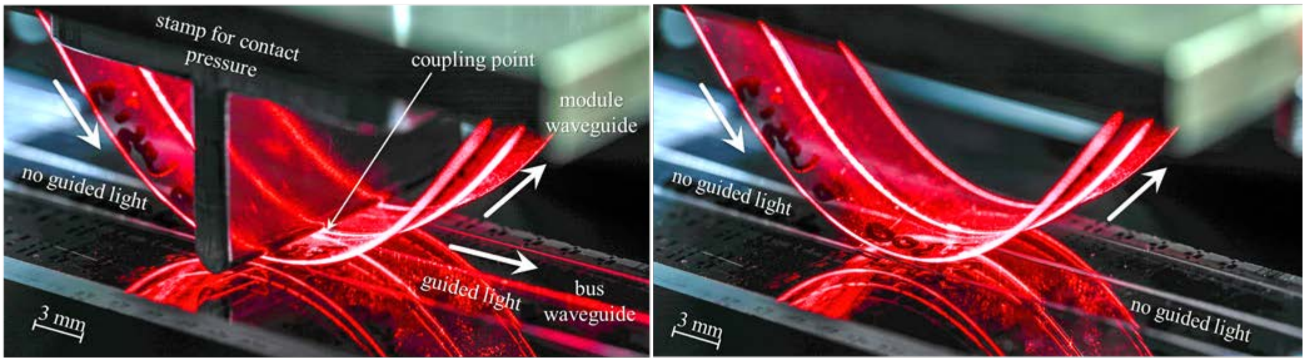

Figure 4. left: Demonstration of the coupling with a red laser source; right: In case the coupling partners are separated, there are no losses at the coupling point. [10]

3. CHALLENGES

In order to integrate POW fabricated with the OPTAVER process for transmitting high amount of data, there are still some challenging issues, which have to be faced. The first problem concerns the printing of the cladding on top of the core material. In Figure 5 it can be seen that the cladding material stays on top of the cured core. The effect itself is once more based on the interaction between the surface energy of the solid core and the surface tension of the liquid cladding material. In this case the surface tension of the core is low so a defined amount of cladding material stays exactly on top. The fluid itself tries to reach the status of minimal energy and begins to split up in single droplets after printing, the so called bulging. If these droplets get too big, the surface energy of the core is not anymore high enough to stop the cladding from dripping off (this effect can be seen in Figure 5 top image). This observation can also be made with the reverse effect leading to a drip off of the cladding material. [11]

The task is to find suitable materials which match together, so that a small cover over the complete core is produced. Another approach is to bring up more material than needed and try to harden the liquid by UV-light before it drips off.

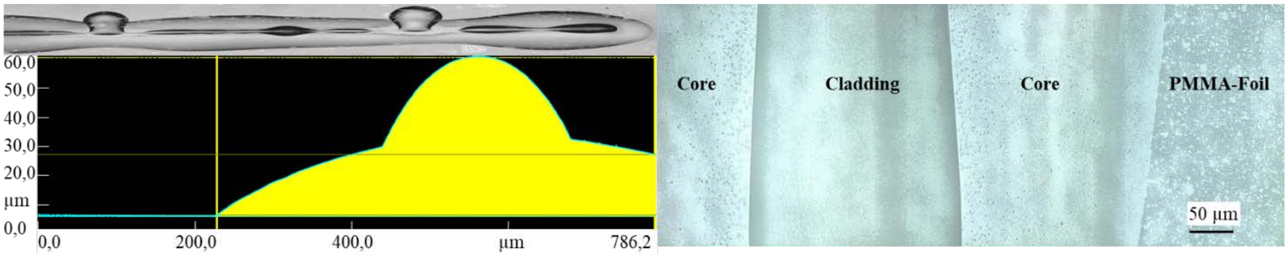

Figure 5. Different illustrations of the cladding material building up a new structure on top of the core or dripping off

One of the main advantages of the OPTAVER process is being able to print waveguides on three dimensional surfaces. Right now this is limited by the flexographic printing of the conditioning lines on planar film substrates. To overcome this problem a thermoforming step can bring the conditioned film substrate into a solid 3D geometry. Afterwards the process chain can continue as usual (see Figure 2). Using most other common technologies for producing POW the whole waveguide would have to be formed while in OPTAVER process only the conditioning lines have to become expandable, preventing the core material from mechanical stress. Hence, the optical quality is expected to be higher.

The conditioning line material is a UV-polymerizing varnish (Actega) which is cross-linked after curing and therefore only ductile in a very limited range. When forming the material underneath, the conditioning lines tear due to excessive plastic deformation. This geometric change prevents a high-resolution fabrication of the waveguide material applied in the next step. A possible solution for this problem is laser structuring and coating the printing form in advance. By this technique, a specialized wetting behaviour on the printing form stamp can be realized. With this functionalization it is possible to control the ink transfer and will allow for printing expandable conditioning lines [6].

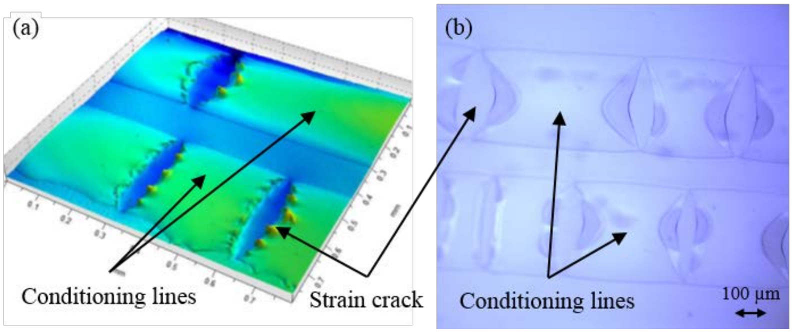

Figure 6. Cracks in conditioning lines in consequence of the thermoforming process (a) confocal microscope measurement, (b) microscopic image. [6]

As already shown in chapter 2, the AOBC works for planar waveguide applications. Furthermore, a technology for a packaging solution is to be developed, which makes it possible to ensure a defined coupling rate for the bus coupling, regardless of the location of the coupling and the nature of the surface, similar to setup shown in Figure 7. This is to ensure that the component / module assembly is independent of a coupling in the plane to a free coupling on three-dimensional circuit carriers. In addition, a robust and reliable component mounting technology is to be developed. To do this, a component mounting process (e.g., Flip Chip Bonder) will be combined with the Adaptive Optical Bus Coupler methodology.

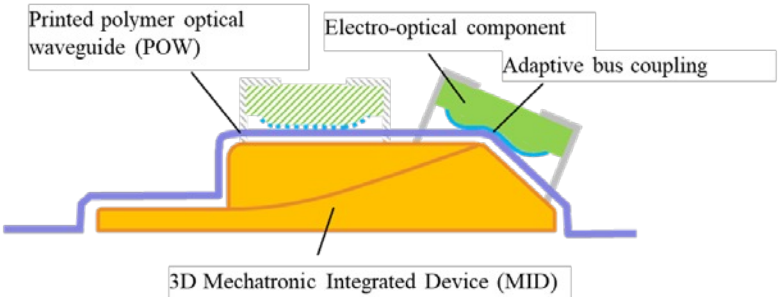

Figure 7. Example of the adaptive coupling of an electro-optical component to a straight or curved surface of a three-dimensional wiring substrate; The goal is to ensure always the same coupling ratio.

4. CONCLUSION

This paper shows the OPTAVER process for printing POW on PMMA-foil substrate as well as the coupling concept for planar waveguide applications. Right now the technology has proven to be able to generate waveguides with measured attenuations of 0.65 dB/cm. Showing their capability for transferring data and signals will follow.

The third dimension is the next frontier which has to be reached. Therefore, the whole process chain has to prove its capability of reaching that goal. The conditioning has to become durable for thermoforming, the AJP-process has to be adapted for printing core and cladding on spatial interconnect devices and the coupling has to allow for connecting onto curved surfaces.

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REFERENCES

[1] OE-A, Organic and Printed Electronics Applications, Technologies and Suppliers, 7th Edition, 6-20, (2017)

[2] Schramm, R., Reitberger, T., Franke, J., “Electrical and Mechanical Investigations on Copper Circuit Paths Coated on Fiber-Reinforced Plastics by Atmospheric Plasma Technology,” Journal of Microelectronics and Electronic Packaging, 12(1), 61-66 (2015).

[3] Seifert, T., Sowade, E., Roscher, F., Wiemer, M., Gessner, T., Baumann, R. R., “Additive manufacturing technologies compared: morphology of deposits of silver ink using inkjet and aerosol jet printing,” Industrial & Engineering Chemistry Research, 54(2), 769-779 (2015).

[4] Wolfer, T., Bollgruen, P., Mager, D., Overmeyer, L., & Korvink, J. G., “Flexographic and inkjet printing of polymer optical waveguides for fully integrated sensor systems,” Procedia Technology, 15, 521-529 (2014)

[5] Soma, K., Ishigure, T., “Fabrication of a graded-index circular-core polymer parallel optical waveguide using a microdispenser for a high-density optical printed circuit board,” IEEE Journal of Selected Topics in Quantum Electronics, 19(2), 3600310-3600310 (2013).

[6] Hoffmann, G. A., Wolfer, T., Zeitler, J., Franke, J., Suttmann, O., Overmeyer, L., “Manufacturing of polymer optical waveguides using self-assembly effect on pre-conditioned 3D-thermoformed flexible substrates,” In Advanced Fabrication Technologies for Micro/Nano Optics and Photonics X, International Society for Optics and Photonics, 10115, 1011503 (2017).

[7] Reitberger, T., Franke, J., Hoffmann, G. A., Overmeyer, L., Lorenz, L., Wolter, K. J., “Integration of polymer optical waveguides by using flexographic and aerosol jet printing,” In Molded Interconnect Devices (MID), 2016 12th International Congress IEEE, 1-6 (2016).

[8] Reitberger, T., Hoffmann, G. A., Wolfer, T., Overmeyer, L., Franke, J., "Printing polymer optical waveguides on conditioned transparent flexible foils by using the aerosol jet technology," In Printed Memory and Circuits II, International Society for Optics and Photonics, 9945, 99450G (2016)

[9] Wolfer, T., Bollgruen, P., Mager, D., Overmeyer, L., Korvink, J. G., "Printing and preparation of integrated optical waveguides for optronic sensor networks," Mechatronics (2015).

[10] Lorenz, L., Nieweglowski, K., Al-Husseini, Z., Neumann, N., Plettemeier, D., Reitberger, T., Franke, J., Wolter, K. J., Bock, K., "Asymmetric optical bus coupler for interruption-free short-range connections on board and module level," Journal of Lightwave Technology, 35(18), 4033-4039 (2017).

[11] Duineveld, P. C., "The stability of ink-jet printed lines of liquid with zero receding contact angle on a homogeneous substrate," Journal of Fluid Mechanics, 477, 175-200 (2003)