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# Characterization of polymer waveguides in cavities on 3D substrates manufactured using the Mosquito method

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### Abstract

The amount of data to be transmitted is increasing in all technical areas, so that optical transmission lines are also becoming more and more interesting on three-dimensional Mechatronic Integrated Devices (3D-MID). An innovative manufacturing approach for optical waveguides is the additive manufacturing using the mosquito method. In this process a liquid polymer, which serves as the cladding material of the waveguide, is applied into a cavity. A micro dispensing needle is then stitched into the liquid cladding. The material for the waveguide core is dispensed into the cladding and the waveguide is realized by a relative movement of the dispensing needle and the substrate. Finally, the entire structure is cured with UV radiation. This method allows it to create waveguides with different core diameters down to single-mode waveguides. The printed waveguides are characterized regarding dimension and optical transmission behavior.

Keywords: optical waveguides, additive manufacturing, mosquito method, dispensing, polymers

## 1. Introduction

Existing MID (Molded Interconnect Device) technologies already enable the integration of electrical and mechanical functions into a single component. The extension of existing MID technologies pursued in this approach, through the incorporation of a manufacturing technique for optical transmission links, contributes to the advancement of the 3D-MID technology field by enhancing its versatility. The "mosquito method" approach aims to be seamlessly integrated into existing process chains, such as the LDS (Laser Direct

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Structuring) method, to open up novel possibilities for the production of optomechatronic hybrid components. The method itself is based on the wet-in-wet dispensing technique, depicted schematically in Figure 1. To create the waveguide core, a dispensing nozzle is inserted into a liquid cladding material, and a relative movement between the printhead and substrate is applied to generate the waveguide core. The polymers are then cured using UV radiation. The printing process takes place in a cavity. Integrating a waveguide in such a cavity offers several advantages over surface mounting. The manufacturing precision of the cavity has minimal influence, as the optical properties only depend on the polymers used for the cladding and core, decoupling them from the component itself. Consequently, there are no inherent restrictions regarding the substrate material. The cavity maintains the dimensional accuracy of the substrate without increasing its surface area. Therefore, the component geometries do not require additional adjustments to accommodate such a waveguide. Moreover, the cavity provides protection against mechanical damage since there is no vulnerable shearing surface. Additionally, the cavity can be further sealed with an additional protective layer, protecting the waveguide from mechanical damage. Furthermore, the adhesion between the substrate and polymer is enhanced, as the cladding makes contact on three sides with the substrate, rather than just one. This also improves protection against vibrations. By utilizing additive manufacturing to integrate waveguides within cavities on the components, the goal is to achieve optical functionalization of 2D and 3D circuit carriers.

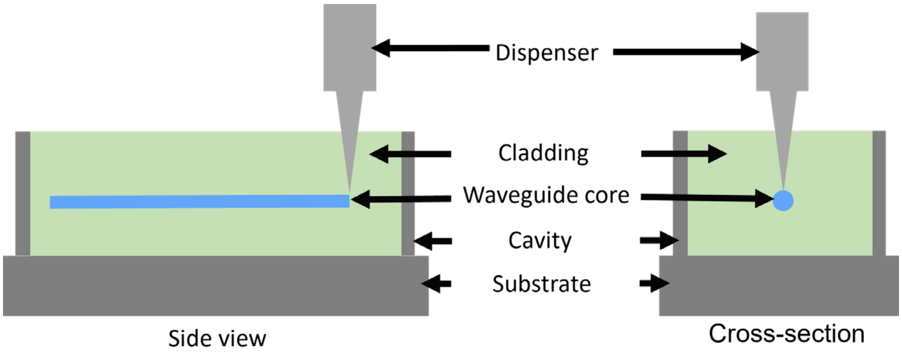


Fig. 1. Mosquito method

The integration of optical transmission links in conventional circuits enables higher data throughput while simultaneously providing resistance to electromagnetic interference and eliminating the need for additional signal shielding for the lines. Additionally, optical transmission links possess inherent galvanic isolation, which scales with the length of the transmission link ($>3\,kV/mm$). This allows these systems to be used in environments with high electric fields and potentially explosive areas. The pursued approach also facilitates the integration of innovative optical measurement techniques. An example of this is the integration of Bragg gratings into the waveguides. In particular, temperature sensors [Zhao et al., 2007] and strain sensors [Kelb et al., 2015] can be mentioned, which can be manufactured in large quantities at low cost.

## 2. Polymer waveguides in cavities using the Mosquito method

### *2.1. Polymer waveguides*

The integration of optical waveguides on three-dimensional electrical circuit carriers is a topic of intensive research, with various competing methods being discussed. In general, a distinction is made between waveguides that need to be fabricated on a substrate and waveguides that can be directly applied to the component surface. Substrate-based waveguides employ planar fabrication processes such as flexographic printing [Wolfer et al., 2016] or hot embossing [Mizuno et al., 2003, Rezem et al., 2014]. In a subsequent step, the substrate can be thermoformed to adapt it to the component geometry [Hoffmann et al., 2020]. The advantage of this approach lies in its high production volume and therefore low cost. The disadvantage is the requirement for a substrate that needs to be additionally applied to a three-dimensional component. This disadvantage is mitigated by fabrication methods that are directly applied to the component surface. In dispensing onto the workpiece, the workpiece serves as the lower cladding [Soma at al., 2013]. In contrast, the mosquito method involves dispensing the waveguide core into a still liquid cladding, which is then cured together with the cladding using UV radiation. This leads to reduced scattering losses due to lower surface roughness and enables the realization of smaller cross-sections. The disadvantage of all dispensing methods is that they involve a serial manufacturing process. However, dispensing is ideal for spatial circuit carriers as it can be applied even on complex 3D components. There is already a wide range of polymers available on the market that can be used to fabricate dispensable and UV-curable optical waveguides. However, a precisely matched core-cladding combination is required in terms of refractive index and viscosity.

### *2.2. The mosquito method*

The mosquito method is used to integrate optically contacted waveguides into cavities on a 3D-MID component through additive manufacturing. The process chain is schematically illustrated in Figure 2. The first step (a) involves the fabrication of the actual substrate with cavities in which the waveguides are printed. The substrates can be additively manufactured. Alternatively, the cavities can be integrated using a laser or adapted injection molds. In the second step (b), the cavity is filled with the liquid cladding polymer. This can be done manually or with a dispensing system that dispenses the cladding polymer along the cavity. In the third step (c), a thin dispensing nozzle is inserted into the still liquid cladding material and dispenses the actual waveguide core. Subsequently (d), the cladding / core composition is cured using UV radiation. Finally (e), the end faces are prepared, and the waveguides are assembled.

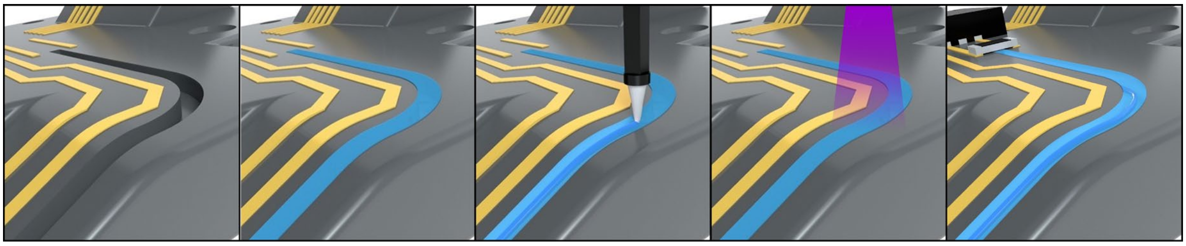

(a) Substrate with cavity (b) Printed waveguide cladding (c) Printed waveguide core (d) UV - irradiation (e) Complete assembly

Fig. 2. Mosquito method process chain (a) substrate with cavity; (b) printed waveguide cladding; (c) printing of waveguide core; (d) UV irradiation; (e) complete waveguide with assembly

For single-mode waveguides, precise control of the dispensing speed is required to achieve a constant waveguide diameter below *10 µm*, matching the dispensing flow rate. In addition to a highly accurate dispensing machine, suitable photopolymers are also needed. Both the core and cladding materials must possess high viscosity to prevent mixing. Furthermore, the core material must have a higher viscosity than the cladding material to ensure displacement of the cladding and the formation of a symmetrical cylinder [Yasuhara et al., 2017].

### *2.3. Experimental Setup*

The following explains the individual components of the experimental setup in detail. Figure 3 shows the schematic experimental setup. The printing system consists of a pneumatic dispensing unit, the dispensing print head, three axes, UV - irradiation and a process monitoring and illumination unit. Furthermore, a computer is used to simplify the operation of the system.

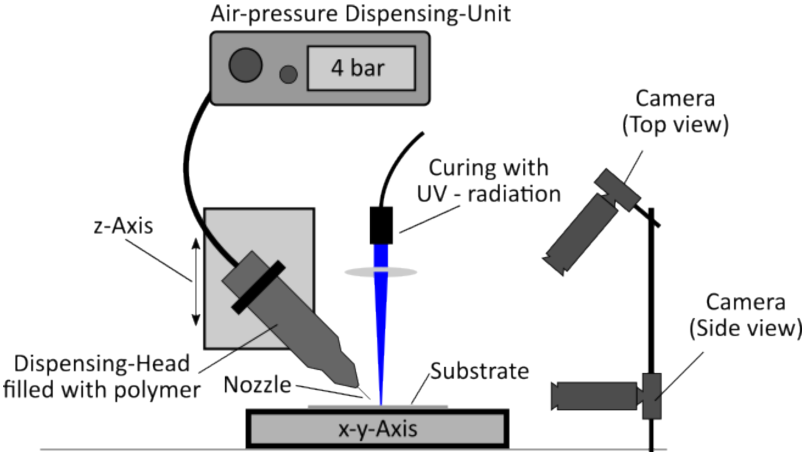


Fig. 3. Experimental Setup

For material dispensing a programmable pneumatic precision dispensing system by Nordson EFD is used. The device offers various signal input and output options that can be used for process automation. The compressed air is supplied to the cartridge through a hose attached to a cartridge adapter. The cartridge contains the dispensing material. To dispense material, a nozzle is connected to the connector of the cartridge. For dispensing liquid monomers, the dispensing system is used in combination with small metal or glass dispensing nozzles. Nozzles with inner diameters ranging from millimeter down to micrometer are available. The print head is positioned using a linear z-axis. For the actual printing process, the system is filled with the monomers and positioned over the substrate. The substrate is moved at a constant speed using a linear axis relative to the dispensing nozzle during the printing process. In addition to the material properties of the polymer and the diameter of the nozzle, the key process parameters are the pneumatic pressure applied to the dispensing system and the feed rate of the axis during the printing process. Since the dispensing nozzle needs to be brought very close to the substrate, a tilting stage has been integrated into the experimental setup. Therewith it is possible to tilt the substrate in two angles. This simplifies the printing process for larger samples.

To monitor the process, particularly the relative position of the dispensing needle to the substrate, two camera systems are utilized. One camera provides a side view of the experimental setup, while the second camera offers a top-down view. The positioning of the dispensing needle relative to the test substrate is manually adjusted using the camera images.

## *2.4. Substrates*

Different additive manufacturing processes are utilized to produce test substrates. These processes include Fused Filament Fabrication (FFF), Stereolithography (SLA), Selective Laser Sintering (SLS) and Multi Jet Modeling (MJM). Various shapes and sizes of cavities are being investigated. Figure 4 (a) illustrates a test specimen featuring triangular, circular, and rectangular cavities. The cavities are manufactured with diameters ranging from *0.1 mm* to *1 mm*. To make the end faces of the waveguide visible, substrates with predetermined breaking points are produced (see Figure 4 (b) and (c) for comparison). These points are spaced at intervals of *5 mm*, allowing for examination of the waveguide at different locations after breaking. For the actual waveguides, two cavities with a width of *5 mm* and a height of *1 mm* are included on top of the substrate. However, the dimensions of these features can be varied.

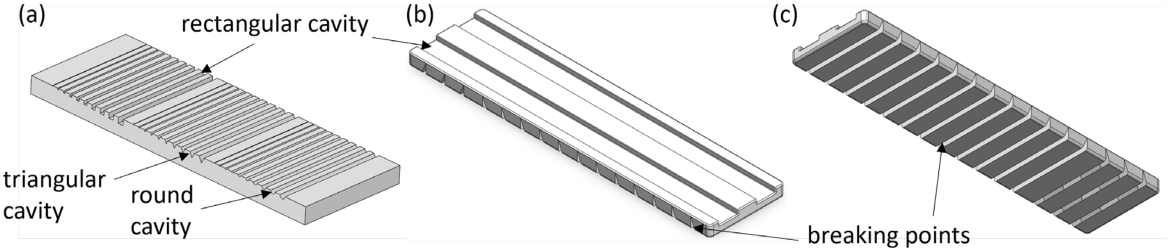
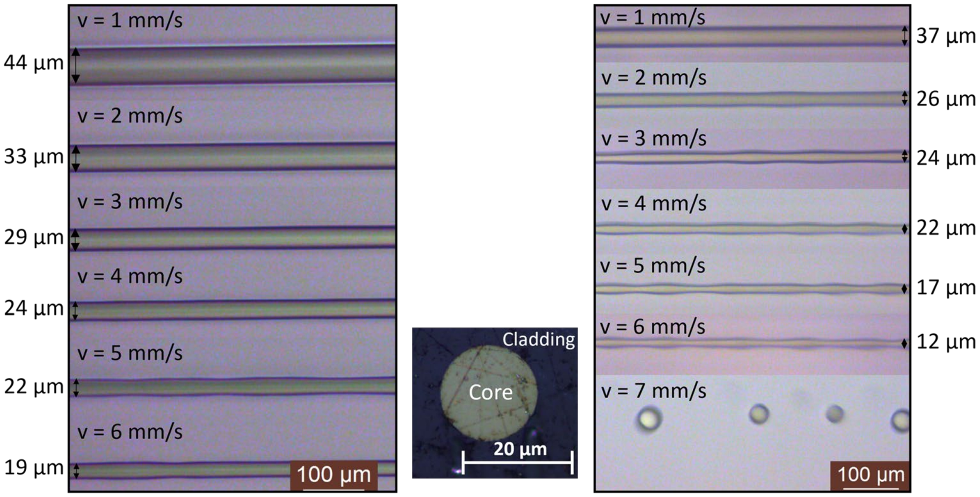


Fig. 4. (a) Substrate with cavities in various shapes and dimensions; (b) Substrate with cavities and fractures (top view); (c) Substrate with cavities and fractures (backside)

## *2.5. Results*

For the waveguide cladding a photo polymer from Jänecke+Schneemann Druckfarben GmbH (J+S) is used. The hybrid polymer Ormocore from Micro Resist Technology GmbH is used for the core. Figure 5 displays waveguides produced using the mosquito method. The waveguides were printed using two different pressures (*0.4 bar* and *0.3 bar*) and various printing speeds from *1 mm/s* to *7 mm/s*. In Figure (a), it is evident that the core diameter decreases with increasing printing speed. Waveguides with diameters ranging from *44 µm* to *19 µm* were successfully fabricated using these process parameters. Furthermore, it is noticeable that the process becomes more unstable at higher speeds, resulting in fluctuating diameters along the waveguide. At lower pressure (c), the instabilities are more pronounced, and even process termination occurs at high speeds ((c) bottom). Figure 5 (b) presents a cross-section of a printed waveguide, emphasizing its circular shape. The visible scratches on the image were results of the mechanical processing of the cross-section. The printing experiments were conducted using a dispensing nozzle with an inner diameter (ID) of *30 µm*.



(a) Printing pressure = 0.4 bar (b) Cross-section (c) Printing pressure = 0.3 bar

Fig. 5. (a) Printing results at 0.4 bar pressure and increasing printing speed; (b) cross section of printed waveguide; (c) printing results at 0.3 bar pressure and increasing printing speed, all Results printed with 30 µm ID Nozzle

Figure 6 shows the frontal face of a waveguide fabricated using the mosquito method on a substrate shown in Figure 4 (b) and (c) within a cavity. To visualize the frontal surfaces of the waveguide, the substrate, cladding, and core composition are broken at the designated position. The waveguide core with a diameter of approximately *41 µm* is clearly visible through transmitted light microscopy (a) and reflected light microscopy (b). Figure 6 (c) depicts a top view of the same waveguide. The waveguide was manufactured using a dispensing nozzle with an inner diameter of *110 µm*, a printing speed of *5 mm / s*, and a pressure of *1 bar*. Ormocore is utilized as the core material, while a polymer from J+S is used as the cladding polymer.

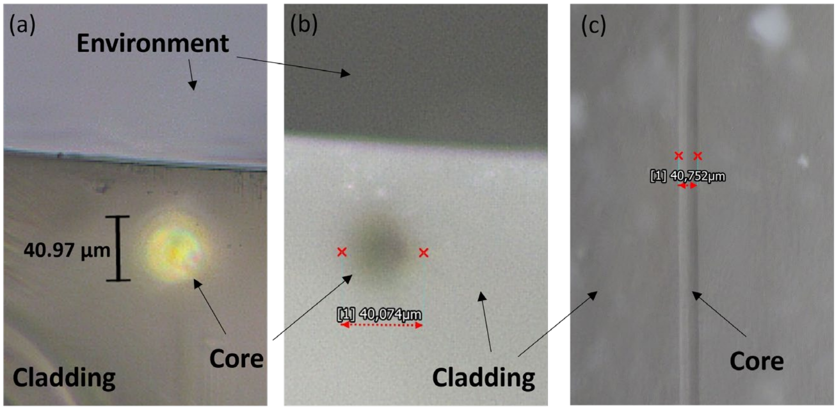


Fig. 6. Waveguide visible through (a) transmitted light microscopy (cross-section); (b) reflected light microscopy (cross-section); (c) reflected light microscopy (top view)

Figure 7 illustrates the successful demonstration of light transmission through a waveguide manufactured using the mosquito method with a diameter of *41.6 µm*. While the beam profile depicted in Figure 7 (a) may not appear perfect yet, the successful transmission of light through the waveguide validates its functionality and potential for further improvement.

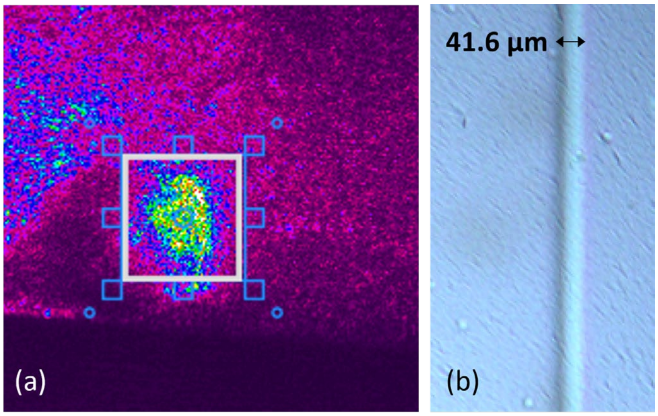


Fig. 7. (a) Beam profile of printed waveguide; (b) Top-view of printed waveguide seen in (a)

## 3. Summary and Outlook

In summary, this study has successfully demonstrated the feasibility of fabricating functional waveguides using the mosquito method as an innovative technique on additive manufactured substrates with cavities. This has opened new possibilities for integrated photonics, with promising implications for various applications. While functional waveguides have been achieved, future efforts will focus on the critical task of preparing the waveguide end facets to minimize surface roughness. Improving the surface quality is crucial for optimizing the coupling efficiency and signal integrity of waveguide-based devices. Another significant challenge lies in the assembly and precise positioning of diodes within the waveguides. The integration of diodes requires robust and reliable techniques to ensure accurate light coupling and minimal signal loss. Future research will concentrate on developing novel assembly and alignment methods to address this challenge effectively. Looking ahead, the field of waveguide fabrication will continue to advance, aiming to overcome the remaining obstacles and enhance overall performance. This includes further refinement of surface preparation techniques, exploration of advanced packaging methods for diode integration, and improving the reliability and scalability of waveguide-based systems.

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