

Integration of Multi-Lithography Technologies for the Fabrication of Flexible Optical Link

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Abstract—The advancement in demand for high bandwidth energy-efficient communication in the data centre and edge cloud servers needs a viable optical interconnection solution to cope with the demands. Therefore, the presented study describes the concept of flexible multi-mode waveguides (MM-WGs) as an optical link for co-packaged optics. It evaluates three lithography technologies; UV-lithography, 2 photon polymerization direct laser writing process (2PP-DLW), and nano-imprint lithography (NIL) for the fabrication of flexible MM-WGs. The UV-lithography and 2PP-DLW process were evaluated for the fabrication of MM-WGs and micro-mirrors, respectively, for the master pattern of the NIL stamp. The NIL evaluates the imprinting of the MM-WGs with micro-mirrors at either end on the flexible and transparent PEN substrates with a low-loss OrmoClad lower cladding layer. There are five different cross-sections from $10 \times 10 \mu m^2$ to $50 \times 50 \mu m^2$ of MM-WGs with micro-mirrors were imprinted. Additionally, it presents the importance of integrating multi-lithography technologies to fabricate flexible optical links where a 2PP-DLW process shows the best results for printing μm -scale optical components. On the other side, UV-lithography with SU-8 gives the foremost definition of the master for the polymeric MM-WGs. Furthermore, NIL offers the industrial mass-production option alongside prototyping.

Index Terms—MM-WGs, micro-mirror, NIL, flexible substrate, multi-lithography

I. INTRODUCTION

The increasing demand for the Internet of Things (IoT), cloud computing, cloud storage, and energy-efficient communication in data centres necessitates an alternative solution to electrical interconnects. However, the miniaturization of semiconductor industries, driven by Moore's Law [1], has made it challenging to fabricate high-speed and energy-efficient electrical interconnects using existing technologies. Furthermore, scaling down copper interconnects has resulted in increased resistivity compared to bulk counterparts due to electron migration at the grain boundaries [2]. Nevertheless, significant advancements have been made in optical interconnects over the past decades, thanks to their potential for high bandwidth and energy-efficient communication. Optical cables

have already demonstrated potential for long-distance communications. Additionally, a previous study [3] highlighted the application of single-mode waveguides (SM-WGs) for short-distance communications at the interposer level, utilizing a hybrid-lithography approach that combines UV-lithography and 2PP-DLW processes to fabricate SM-WGs with micro-mirrors for out-of-plane communication. However, the slow nature of the 2PP-DLW process makes mass production of micro-mirrors challenging without advancements in processing tools. Nevertheless, to counter the problem, [4] shows the application of NIL for the fabrication of SM-WGs with micro-mirrors.

Flexible optical links present promising applications for high-bandwidth and energy-efficient communication in co-packaged optics. Therefore, this work discusses the concept of multi-lithography for fabricating flexible optical links. The concept mainly focuses on fabricating MM-WGs with micro-mirrors at each end on a flexible PEN substrate using UV-NIL to transfer the signal out-of-plane. Multi-lithography refers to three lithography processes used to fabricate these flexible optical links: UV-lithography, 2PP-DLW process, and UV-NIL technology. The integration of these technologies aims to leverage their specific capabilities with suitable materials to create customized and efficient structures for flexible optical links. To replicate the MM-WGs with micro-mirrors onto the low-loss OrmoCore polymer, a master stamp needed to be fabricated. As described in a previous study [5], UV-lithography with SU-8 polymer was employed for the fabrication of the master stamp, providing precise 90° sidewall angles and smooth structures with nanoscale roughness. Conversely, the 2PP-DLW process with IP-DIP resin, explicitly designed for printing applications, enables better structural definition with sharp edges for the micro-mirrors and faster printing of these structures with lower surface roughness.

In this study, five different cross-sections ranging from $10 \times 10 \mu m^2$ to $50 \times 50 \mu m^2$ of optical links were successfully imprinted on the OrmoCore polymer, which serves as the

core layer for MM-WGs over a low-loss OrmoClad lower cladding layer on a flexible substrate. Section II provides an introduction to the concept of integrating multi-lithography, while section III discusses the experimental results. Sections IV cover the conclusion and future outlook of the work.

II. INTRODUCTION TO THE CONCEPT OF MULTI-LITHOGRAPHY TECHNOLOGIES FOR FLEXIBLE OPTICAL LINK

As previously mentioned, the concept of integrating multi-lithography technologies aims to maximize the performance of each technology with the most suitable materials. Fig. 1 depicts the processing steps of fabricating flexible optical links using multi-lithography technologies. Firstly, as shown in Fig. 1(a), SU-8 waveguides were fabricated using a specially designed mask that ensured uniform pressure distribution for achieving a nearly uniform residual layer at the end of the UV-NIL process. The fabrication of SU-8 waveguides followed a standard procedure described in reference [5], employing UV-lithography. After fabricating the waveguides, micro-mirrors were created at each end using the 2PP-DLW process with IP-DIP resin, as illustrated in Fig. 1(b). The alignment accuracy during micro-mirror fabrication was within $\pm 1 \mu m$, and the roughness was below 0.1λ .

Once the master with MM-WGs and micro-mirrors was prepared, an anti-sticking layer was applied using the provided silanization solution. Subsequently, the stamp was fabricated by drop-casting OrmoStamp polymer onto the pattern master, as shown in Fig. 1(c). Due to the low viscosity of OrmoStamp at $25^\circ C$, which is $0.5 \text{ Pa}\cdot s$, it settled automatically through the openings under the weight of the glass substrate. For the subsequent steps illustrated in Fig. 1(d) and 1(e), substrates were prepared by bonding a flexible PEN film onto the silicon wafer, followed by the coating of the lower cladding layer.

The next steps involved the drop-casting method, where small droplets of $0.01\text{-}0.02 \text{ gm}$ of OrmoCore-OrmoThin polymer were deposited on the prepared substrate to form the core layer, as depicted in Fig. 1(f). Before contacting the stamp with the droplet, it was coated with the anti-sticking coating trichloro-(1H,1H,2H, 2H-perfluorooctyl)-silane provided by Sigma-Aldrich. After curing, as shown in Fig. 1(g), the stamp was de-bonded from the substrate. Finally, the flexible PEN film, along with the layer of MM-WGs, was also de-bonded from the silicon substrate to obtain the flexible optical link.

III. EXPERIMENTAL RESULTS AND DISCUSSION

In the initial stage, as outlined in reference [5], a master for the NIL stamp was prepared. The fabrication of the master patterns involved two steps. In the first step, SU-8 MM-WGs were fabricated using UV lithography. To achieve MM-WGs with straight 90° sidewalls and square cross-sections, different combinations of power and timing were experimented with, and successful results were obtained at 225 mJ/cm^2 for all cross-sections of WGs. Fig. 2 [5] illustrates the results

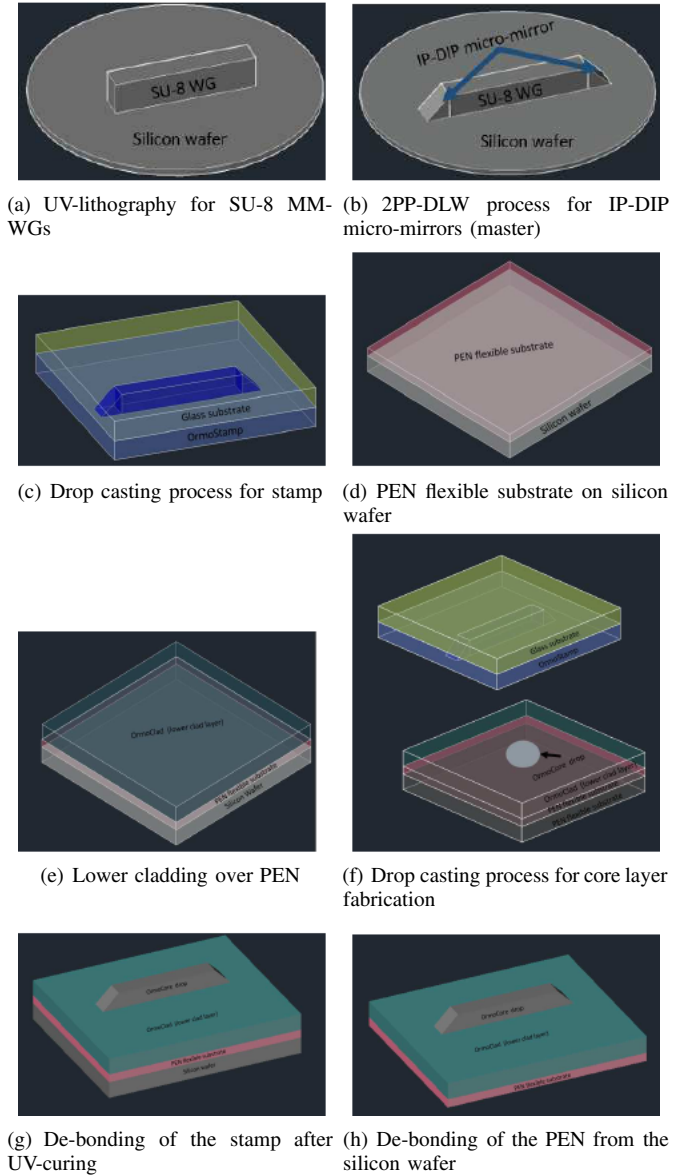


Fig. 1. Processing steps for the fabrication of flexible optical links using multi-lithography technologies

for $30 \times 30 \mu m^2$ of cross-section of the MM-WGs. Additionally, [5] shows the results for all other cross-sections of MM-WGs. One advantage of using SU-8 is its compatibility with contact mode lithography, which ensures the formation of 90° sidewalls and smooth MM-WGs surfaces, facilitating easy demolding during NIL and enabling better optical signal transmission.

In the second step, the micro-mirrors were printed using IP-DIP resin and the 2PP-DLW process, achieving an alignment accuracy of $\pm 1 \mu m$. The IP-DIP resin, developed by Nano-scribe GmbH & Co. KG, is specifically designed to enable faster printing with sharp structural contours. The experimental procedure and processing parameters for this step can be found in reference [5]. Fig. 3 [5] displays the printed mirrors located

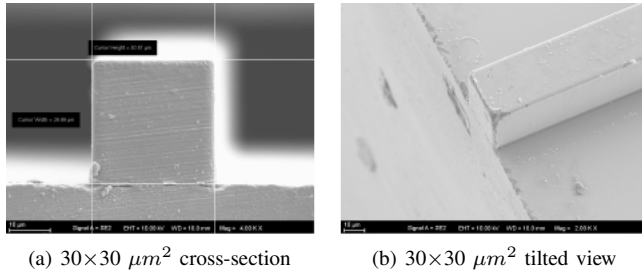


Fig. 2. Patterned $30 \times 30 \mu\text{m}^2$ cross-section of SU-8 MM-WGs by UV-lithography [5]

at the ends of the SU-8 MM-WGs for $30 \times 30 \mu\text{m}^2$ cross-section, serving as the pattern master for the NIL process.

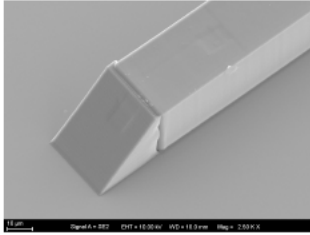


Fig. 3. 2PP-DLW printed $30 \times 30 \mu\text{m}^2$ micro-mirrors with IP-DIP resin at the end of the SU-8 MM-WGs [5]

In the subsequent step, the pattern master was coated with an anti-sticking layer using Silanization Solution I, n-Hexane, and I-Octane from Sigma-Aldrich. The silanization solution reacted with the silicon surface, forming a solid covalent bond through a condensation reaction and resulting in the presence of an organosilane molecule on the surface. This organosilane layer provided a highly hydrophobic surface. The pattern master was immersed in the silanization liquid for 20 minutes to achieve this hydrophobic surface. Subsequently, it was immersed in n-Hexane and I-Octane for 15 minutes each to remove any residual contamination or unreacted silane molecules. These non-polar solvents, n-Hexane and I-Octane, did not alter the hydrophobic properties of the organosilane surface on the pattern master.

For the next step, a glass substrate measuring $50 \times 50 \text{ mm}$ and 3.8 mm thick was prepared. It underwent a standard cleaning process, followed by plasma treatment at 200 W for 3 minutes. An OrmoPrime layer was then spin-coated onto the glass substrate at 4000 RPM for 60 seconds, resulting in a thickness of approximately 150 nm . This OrmoPrime layer improved the adhesion of the OrmoStamp resin to the glass surface. The glass substrate was then baked on a hot plate at 150°C for 5 minutes.

Next, the stamp was fabricated using a drop-casting method by using the master pattern. A precise amount (0.01 gm in this case) of OrmoStamp was dropped onto the pattern master using a syringe. Degassing was performed before or after dropping the resin to remove any trapped air bubbles, and a pointed syringe tip also be used to burst the bubbles. Subsequently, the glass substrate, treated with OrmoPrime,

was gently placed upside down to make contact with the OrmoStamp drop on the pattern master. Due to the lower viscosity of the OrmoStamp resin, it spread across the pattern master's surface under the weight of the glass substrate. It took approximately 10 minutes for the resin to completely fill all the patterns on the pattern master. The thickness of the resulting OrmoStamp master depended on the amount of OrmoStamp resin applied initially as a droplet. The manufacturer, micro resist technology GmbH, provides data in [7] on the recommended amount of OrmoStamp resin for a specific substrate size. Once the OrmoStamp was settled, a full exposure at $20 \text{ mW}/\text{cm}^2$ for 50 seconds was performed. To de-bond the pattern master from the glass substrate with the cured OrmoStamp resin, a small force was applied at one of the corners using a sharp blade, resulting in easy demolding. The stamp was further hardened through a 30-minute hard baking process at 130°C . Fig. 4 illustrates the fabricated stamp result. The middle section of Fig. 4 depicts the MM-WGs with micro-mirrors at the ends, while different stamps were fabricated for each of the various cross-sections of the MM-WGs.

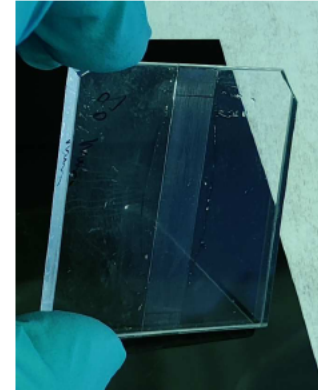


Fig. 4. Fabricated glass-OrmoStamp stamp

In the subsequent process steps, a substrate was prepared by applying double-sided tape to a clean 4-inch silicon wafer. A flexible PEN substrate was then applied to the tape, followed by spin-coating and curing $40 \mu\text{m}$ thick lower-clad layer using OrmoClad polymer.

To facilitate easy demolding after NIL curing, an anti-sticking layer was coated on the glass stamp with OrmoStamp. Trichlor-(1H,1H,2H,2H-perfluorooctyl)-silane (PFOTS) was used for this purpose. A drop of PFOTS was placed beside the glass stamp and the setup was placed in a desiccator, where the pressure was reduced to 0.06 bar to allow for the evaporation of PFOTS over a period of 20 minutes. Subsequently, the glass stamp was hard-baked on a hot plate at 150°C for 15 minutes. During this process, a reaction occurred between the silanol (Si-OH) group in the OrmoStamp and the trichlorosilane (Si-Cl) group of PFOTS. Hydrolysis resulted in the formation of PFOTS-OH, followed by a condensation reaction that formed PFOTS-O-Si-OrmoStamp bonds, providing hydrophobic and oleophobic properties to the stamp.

To minimize the residue layer at the end of the NIL process, a lower thickness of the OrmoCore polymer was required for the core layer. However, OrmoCore alone had a higher viscosity, making it unsuitable for NIL. To address this, it was diluted with OrmoThin in a 1:1 ratio to reduce the viscosity. Since the substrates used in this work were sized at 0.8x50 mm, the spin-coating process was not applicable. Therefore, a drop-casting method was employed. Where, a drop of the diluted OrmoCore-OrmoThin mixture, weighing around 0.01 to 0.02 grams, was gently placed on the prepared substrate. However, covering the entire surface with the polymer is a problem as the viscosity of the OrmoCore is regained after prebaking, which limits the flow of the OrmoCore resulting in an incomplete coating of the substrate while imprinting. Therefore, manually spreading the liquid over the surface was done with a slightly more quantity of the OrmoThin-OrmoCore mixture. After manually spreading the liquid over the surface, a pre-baking step was performed at 85 °C for 2 minutes to evaporate the OrmoThin from the substrate surface. Subsequently, an anti-sticking layer-coated glass stamp was placed upside down, with the treated surface in contact with the spread OrmoCore on the substrate, applying a pressure of 35N for 30 minutes to ensure complete filling of all patterns by the OrmoCore polymer. UV curing was then conducted at 3000 mJ/cm² (20 mW/cm² for 150 seconds). To demold the glass stamp from the substrate, a slight force was applied at the edge of the substrate surface using a sharp blade. Finally, the recommended hard-baking step at 130 °C for 10 minutes was performed to harden the OrmoCore patterns containing MM-WGs with micro-mirrors at either end. Fig. 5 illustrates the imprinted results for the five different cross-sections of MM-WGs with micro-mirrors.

In Fig. 5(a), the OrmoCore MM-WG cross-section of 10×10 μm² is depicted, while a tilted view with the micro-mirror is shown in Fig. 5(b). In Fig. 5(b), a desired square cross-section is observed for the 10×10 μm² MM-WGs, indicating that the shape was successfully preserved throughout the processing steps. However, a residue layer of 980 nm can also be seen. It should be noted that the pressure applied during NIL was limited to 35N, so the main focus was on successfully imprinting the pattern. Some visible dust particles can also be observed, likely from the dicing saw used during the MM-WG cross-section characterization. Nevertheless, the surface of the MM-WGs and micro-mirror appears smooth. Similarly, the imprinted cross-sections of MM-WGs with micro-mirrors, including 20×20 μm², 30×30 μm², 40×40 μm², and 50×50 μm² are shown in Fig. 5(c) and 5(d), Fig. 5(e) and 5(f), Fig. 5(g) and 5(h), Fig. 5(i) and 5(j), respectively. Some defects can be observed around the micro-mirror structures, but they can be easily mitigated by slightly adjusting the processing parameters. However, the shape and roughness values were preserved at the end of the process.

IV. CONCLUSION AND FUTURE OUTLOOK

In this work, the integration of three lithography technologies, namely UV-lithography, 2PP-DLW process, and nanoim-

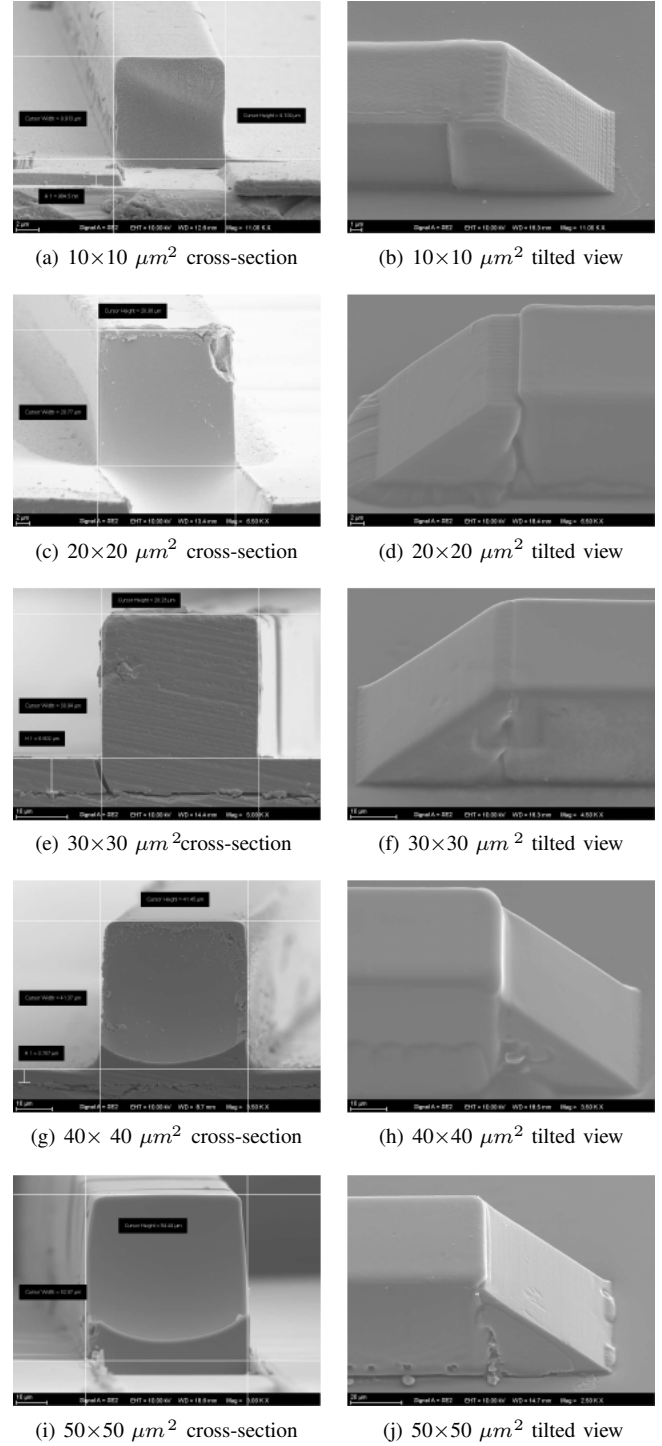


Fig. 5. NIL processed OrmoCore MM-WGs with their cross-sections and micro-mirrors at the end

print lithography, was demonstrated for fabricating MM-WGs with micro-mirrors at both ends to enable out-of-plane signal direction for high-speed co-packaged optics applications. A previously fabricated master with SU-8 MM-WGs and micro-mirrors, created using UV-lithography and 2PP-DLW process, respectively, was utilized in this study. The processing steps involved applying an anti-sticking layer to the previously fabricated master, fabricating a glass stamp from OrmoStamp material, coating the glass stamp with an anti-sticking layer, preparing the substrate, and successfully imprinting the patterns containing MM-WGs and micro-mirrors onto the low-loss OrmoCore hybrid polymer through nanoimprint lithography. The roughness and shape of the structures were preserved throughout the process, with no noticeable effects on their quality. However, some defects were observed around the micro-mirror area, likely arising from the final nanoimprint lithography steps. These defects can be mitigated by making slight adjustments to the process parameters.

For future work, the process parameters will be further optimized to achieve the best possible results from the employed technologies. With improved processing steps in higher-pressure facilities, efforts will be made to minimize the residue layer to an optimum level, enabling clean imprinting with a better pattern-to-defect ratio. Then an etching will be performed to completely remove the residue layer. Subsequently, the optical performance of the MM-WGs with micro-mirrors, along with their mechanical performance, will be characterized.

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