Replication of self-centering optical fiber alignment structures using hot embossing

Evert Ebraert\textsuperscript{a}, Markus Wissmann\textsuperscript{b}, Nicole Barie\textsuperscript{b}, Markus Guttmann\textsuperscript{b},
Marc Schneider\textsuperscript{b}, Alexander Kolew\textsuperscript{b}, Matthias Worgull\textsuperscript{b}, Stefano Beri\textsuperscript{c}, Jan Watté\textsuperscript{c},
Hugo Thienpont\textsuperscript{a} and Jürgen Van Erps\textsuperscript{a}

\textsuperscript{a} Brussels Photonics Team (B-PHOT), Department of Applied Physics and Photonics, Vrije Universiteit Brussel (VUB), Pleinlaan 2, B-1050 Brussels, Belgium.
VUB is a member of Flanders Make;
\textsuperscript{b} Karlsruhe Institute of Technology (KIT), Institute for Microstructure Technology (IMT);
\textsuperscript{c} CommScope, R\&D Optics Advanced Engineering, Diestsesteenweg 692, 3010 Kessel-Lo, Belgium

ABSTRACT

With the demand for broadband connectivity on the rise due to various services like video-on-demand and cloud computing becoming more popular, the need for better connectivity infrastructure is high. The only future-proof option to supply this infrastructure is to deploy “fiber to the home” (FTTH) networks. One of the main difficulties with the deployment of FTTH is the vast amount of single-mode fiber (SMF) connections that need to be made. Hence there is a strong need for components which enable high performance, robust and easy-to-use SMF connectors. Since large-scale deployment is the goal, these components should be mass-producible at low cost. We discuss a rapid prototyping process on the basis of hot embossing replication of a self-centering alignment system (SCAS) based on three micro-springs, which can position a SMF independently of its diameter. This is beneficial since there is a fabrication tolerance of up to ±1 μm on a standard G.652 SMF’s diameter that can lead to losses if the outer diameter is used as a reference for alignment. The SCAS is first prototyped with deep proton writing (DPW) in polymethylmethacrylate (PMMA) after which it is glued to a copper substrate with an adhesive. Using an electroforming process, a nickel block is grown over the PMMA prototype followed by mechanical finishing to fabricate a structured nickel mould insert. Even though the mould insert shows non-ideal and rounded features it is used to create PMMA replicas of the SCAS by means of hot embossing. The SCAS possesses a central opening in which a bare SMF can be clamped, which is designed with a diameter of 121 μm. PMMA replicas are dimensionally characterized using a multisensor coordinate measurement machine and show a central opening diameter of 128.3 ± 2.8 μm. This should be compared to the central opening diameter of the DPW prototype used for mould formation which was measured to be 120.5 μm. This shows that the electroforming and subsequent replication process is possible for complex micro-scale components and could be accurate after optimisation. We characterized the sidewall roughness of PMMA replicas using a non-contact optical profiler, resulting in a root-mean-square roughness of 48 nm over an area of 63.7 μm×47.8 μm. This low sidewall roughness is especially important in the replication of high aspect ratio structures to facilitate demoulding since the sidewalls cause the most friction with the mould insert.

Keywords: alignment, deep proton writing, electroplating, fiber connector, hot embossing, optical fiber, replication

1. INTRODUCTION

With the demand for broadband connectivity on the rise due to various services like video-on-demand and cloud computing becoming more popular, the need for better connectivity infrastructure is high. The only future-proof solution for such high-speed networks is the use of optical fiber and bringing it as close as possible to the end user, ultimately into the subscriber’s home.\textsuperscript{1,2} Deploying “fiber to the home” (FTTH) on a large scale gives rise
to a huge demand for fiber connectivity solutions. These solutions must allow for physical mating of single-mode fibers with very low loss, or in other words with sub-micron alignment accuracy. To this end, we have designed a self-centering alignment system (SCAS) which can center a fiber upon insertion and ensures a good lateral alignment accuracy between two mated single-mode fibers. The SCAS is based on deflectable micro-springs which exert a force on the fiber while it is being inserted. Self-centering fiber connectors can mitigate the effect of the fabrication tolerance (of up to \( \pm 1.0 \, \mu m \)) on the cladding diameter of G.652 standard telecom single-mode fiber, as opposed to more traditional connector approaches making use of ferrules or V-grooves. We propose to make a connector assembly by adding a pre-alignment system to limit the angular misalignment and ensuring physical contact between 2 connected fibers with a controlled buckle of the fiber. Since large-scale deployment of FTTH is the driving force behind this research, low-cost mass-manufacturability of the components is paramount. In addition, they should be compatible with the stringent environmental conditions such as an operating temperature ranging from -40 °C to 70 °C. High-performance plastics compatible with replication technologies such as micro-injection moulding or hot embossing are capable of meeting these requirements. The design of a three-spring SCAS is illustrated in Fig. 1(a). Notice that the central opening is 121 \( \mu m \) in diameter, which is smaller than the nominal cladding diameter of a G.652 SMF (i.e. 125 \( \mu m \)). As such, when inserting a fiber, the cantilevers will deflect and thus exert a force on the fiber causing it to be centered with respect to the alignment structure. Two 700 \( \mu m \)-diameter holes for mechanical transfer (MT)-pins are included in the design. These are high-tolerance alignment pins which are used in commercial fiber connectors such as multiple push-on (MPO) connectors, to which the SCAS design is made compatible. The aspect ratio of the SCAS is 1:5 (100 \( \mu m \) wide and 500 \( \mu m \) deep cavities). In this paper, we discuss the use of hot embossing for the replication of SCAS components. In Section 2, we describe the deep proton writing technology that was used for prototyping the master component in polymethylmethacrylate (PMMA). We also discuss the justified partial metallization of that master component in order to realize a metal mould insert through electroforming and the hot embossing replication of these structures. In Section 3, we describe the results of the hot embossing replication and characterize the replicas in terms of geometry and surface roughness.
2. TECHNOLOGY DESCRIPTION AND EXPERIMENTAL METHODS

2.1 Prototyping by deep proton writing

Deep proton writing is a rapid prototyping technology for micro-optical and micro-mechanical components.\textsuperscript{12} DPW finds its origins in the LIGA technology (Lithographie, Galvanoformung, Abformung)\textsuperscript{13} but uses protons rather than X-rays for the irradiation process. DPW is a direct writing process in which the desired proton beam diameter is selected in a stopping mask and the sample is moved perpendicularly to the proton beam according to a predefined pattern (i.e. the design of the SCAS in this case). The stopping mask consists of two stacked 350 \(\mu\text{m}\)-thick nickel plates with apertures ranging from 50 \(\mu\text{m}\) to 300 \(\mu\text{m}\). This mask can stop protons with an energy of up to 16.5 MeV,\textsuperscript{14} enabling irradiation of PMMA substrates that are up to 2 mm thick.\textsuperscript{15} The concept of DPW is based on the fact that irradiating high-molecular-weight PMMA with highly energetic protons will break the long polymer chains. This can be exploited because it changes the physical and chemical material properties of the unexposed bulk material, allowing these irradiated zones to be selectively etched away.\textsuperscript{12} High-quality prototyping of (arrays of) micro-holes,\textsuperscript{16} micro-pillars\textsuperscript{14} and micro-mirrors with optical quality sidewalls\textsuperscript{12} is all possible with DPW. During an irradiation the protons scatter within the substrate material, causing a slightly conical shape when irradiating micro-holes for example.\textsuperscript{16} In our case the conical shape is an asset, since it both facilitates the fiber insertion in the SCAS and the demoulding of replicas. The DPW-prototyped master of a three-spring SCAS structure is shown in Fig. 1(b). Since the SCAS is designed with a thickness of 500 \(\mu\text{m}\) a proton energy of 12 MeV was used, as this is sufficient to guarantee full traversal of the protons through the sample and higher energies would cause a higher amount of surface damage due to stray protons and the long irradiation times required for the SCAS. Since the smallest cavity in the SCAS is 100 \(\mu\text{m}\) wide, the resulting aspect ratio is 1:5. This component was irradiated using the smallest available proton beam diameter of 50 \(\mu\text{m}\) to be able to pattern the finest features of the design in the central hole region in the SCAS. The proton fluence was optimized to \(5.2 \times 10^8\) protons per \(\mu\text{m}^2\) to achieve the desired dimensional shape. The total irradiation time for two 700 \(\mu\text{m}\) diameter alignment holes and the SCAS itself is about 5 hours. Hence it is clear that DPW is a costly and time-consuming process, ideally suited for rapid prototyping but not for large volume production.

2.2 Mould insert formation

DPW prototypes can be used as a master for generating a metal mould by applying a combination of joining technology and electroforming. We have previously shown the successful replication of DPW-prototyped micro-mirror structures using this methodology.\textsuperscript{17} However, the current self-centering fiber alignment structures contain through-holes and small cavities, which could induce errors like incomplete filling or underplating during the electroforming process. To avoid these possible errors, we have developed a justified partial metallization process for the mould formation.\textsuperscript{18} This process requires the polymer prototype to be attached to a copper substrate. A dip method was used to apply adhesive to the prototype structure, which is subsequently pressed against the copper substrate. Even with this special dip method some excessive adhesive covered the copper substrate in the smallest features of the SCAS. Laser ablation was used to remove the adhesive in these through-holes and reveal the copper substrate for subsequent electroforming. To ensure that the electroforming starts by filling the small through-holes and only after filling those, covers the rest of the structure, a seed layer is deposited on the structure with physical vapour deposition through a mask.\textsuperscript{18} This allows us to avoid defects like void spaces or loose parts in the electroformed nickel mould. The final step of the mould insert fabrication consists of cutting the mould insert to its desired dimensions by wire electron discharge machine cutting. A scanning electron microscope (SEM) image of the mould insert is shown in Fig. 2(a).

2.3 Replication by hot embossing

The mould insert is placed in the upper part of the hot embossing equipment (a HEX03 from Jenoptik Mikrotechnik GmbH). The lower part of the hot embosser consists of a demoulding plate with a high surface roughness (sandblasted stainless steel) to facilitate the demoulding of replicas. Both the upper and lower part can be heated up to 280 °C and can maintain a pressure of up to 200 kN. We aim to make replicas in PMMA, since this will allow us to compare replicas with the original prototypes in the same material and since we have previous experience with hot embossing this material. The embossing process starts with placing a PMMA substrate on the demoulding plate. The upper and lower part of the embosser close and form a vacuum chamber, which
is evacuated to a pressure below 100 mbar. The mould insert and demoulding plate are subsequently heated up to 180 °C. Once this temperature is reached the actual embossing happens with a force of 50 kN, which is maintained for 5 minutes. Then the whole system is cooled down to 80 °C while holding the force constant at 50 kN in order to minimize the effect of shrinkage of the polymer and to avoid void spaces from forming in the embossed structure. After cooling down, the upper and lower parts are pulled apart and the replica sticks to the demoulding plate because the friction of the replica with the sand-blasted demoulding plate is larger than the friction with the mould insert. The total cycle time for a SCAS component to be replicated, is about 30 minutes. A SEM image of a silver-plated replica can be seen in Fig. 2(b). Parts replicated with hot embossing inherently possess a residual layer underneath the component, as can be seen in Fig. 3(b). Since fibers needs to penetrate the SCAS we need to remove the residual layer for our purposes. The removal of the residual layer is currently being investigated.

3. RESULTS

3.1 Geometrical characterization

The mould insert fabricated by electroforming a DPW prototype, as described in section 2.2, is measured using a Werth UA-400 multisensor coordinate measure machine (CMM). Replicas made from this mould insert by hot embossing, as described in section 2.3, are also characterized using this CMM. For the geometrical characterization we measure two critical features of the SCAS: the size of the central opening and the size of the MT-pin holes as indicated in Fig. 1(a). When the central opening is larger than 126 µm in diameter, the structure will no longer exhibit any self-centering functionality since the cladding diameter of a G.652 SMF is 125±1 µm. The smaller the central hole becomes, the more force will be required to insert a fiber. Therefore it is important that the central hole diameter is in the range of 121-124 µm to avoid nonfunctional SCAS structures. In an MPO-compatible connector assembly, the MT-pin holes are used to align two connector assemblies in order to make a physical fiber connection (mechanical splice). Hence the MT-pin hole size and position are also crucial to the functionality of the SCAS. In our case two SCAS connector assemblies can be connected or one SCAS connector assembly can be connected to an MPO connector. The results of the electroformed mould insert are shown in Tab. 1. Regarding the central hole the mould insert is in spec (i.e. inside the 121-124 µm range). For the MT-pinhole though, the mould is slightly out of spec (i.e. outside the 699-701 µm range). In Fig. 2(a) we can see that the mould insert shows rounded features, caused by an excess of adhesive that we were
Figure 3: Microscope image of (a) the top-side and (b) a hot embossed SCAS replica in PMMA with residual layer cut down to a size (∼15 mm × ∼20 mm).

Table 1: Central hole and MT-pin hole diameter measured for a prototype, for the mould insert that was created from that particular prototype and for the replicas made in PMMA. The amount of replicas measured is mentioned in brackets.

<table>
<thead>
<tr>
<th></th>
<th>Central ⊙ (µm)</th>
<th>MT ⊙ (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DPW prototype</td>
<td>120.5</td>
<td>701.5</td>
</tr>
<tr>
<td>Mould insert</td>
<td>122.9</td>
<td>700.2</td>
</tr>
<tr>
<td>PMMA replicas (5)</td>
<td>128.3 ± 2.8</td>
<td>713.0 ± 10.7</td>
</tr>
</tbody>
</table>

unable to remove with laser ablation. This will cause the SCAS replicas’ spring cavities (shown in Fig. 2(b)) to not be fully open over the whole depth of the structure, thus increasing the spring-constant (stiffness) and the force required to insert a fiber in the SCAS. This is not problematic though, since we are still able to insert bare SMFs in the cavities. Considering the replicas, we can see that both the central hole and MT-pin holes are slightly out of spec (i.e. outside the 121-124 µm and 699-701 µm range for the central opening hole and MT-pin hole respectively). From the geometrical data of the mould insert and replicas (see Tab. 1) we can estimate the shrinkage of the PMMA replicas fabricated with this mould insert to be ~1.5 %, based on the MT-pin hole diameter. The effect of shrinkage on the central opening diameter is larger (~3.5 %) but it should be noted that the central opening is defined by three separate complex micro-structures, which can affect the total resulting shrinkage behaviour. Note that it is possible to compensate for the shrinkage by modifying the design of the DPW prototypes. This way the mould insert electroformed from this compensated prototype will have an under-dimensioned central opening and MT-pin hole diameter, such that the replicas created from this mould will shrink to their target dimensions after the hot embossing replication.

3.2 Surface roughness measurements

We study the surface roughness of the replicas, since it has a large influence on the demoulding step of the hot embossing process and on the fiber insertion into the resulting replicas. The sidewall and top side of the replicas were measured using a Bruker Contour GT-I non-contact optical profiler. The roughness of the top-side and inner sidewalls is a result of the electroformed mould’s roughness, which in turn is determined by the surface roughness of the PMMA sheets used for DPW and by the DPW process itself, respectively. Hence we expect the top side and inner sidewalls to show a low surface roughness. The root-mean-square surface roughness, defined as \( R_q = \sqrt{\frac{1}{n} \sum_{i=1}^{n} y_i^2} \), where \( y_i \) is the vertical distance from the mean height line to the \( i^{th} \) data point) of three randomly selected areas of 63.7 µm × 47.8 µm was determined and averaged per replica under
<table>
<thead>
<tr>
<th>$R_q$ (nm) (#measured)</th>
<th>PMMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top-side</td>
<td>57 ±18 (4)</td>
</tr>
<tr>
<td>Inner sidewall</td>
<td>48 ±10 (2)</td>
</tr>
</tbody>
</table>

investigation. Four PMMA replicas were investigated for their top side surface roughness and two were cut open by micro-milling to investigate their inner sidewall surface roughness. The results are shown in Tab. 2 and from this data we can confirm that the top side and inner sidewall surface roughness is indeed low. The low sidewall roughness is beneficial, not only for the demoulding of replicas (since the sidewalls cause the most friction with the mould insert during demoulding), but also for having minimal friction during fiber insertion in the replicas during connector assembly.

4. CONCLUSIONS

We have shown that a deep proton writing (DPW) fabricated polymethylmethacrylate (PMMA) prototype of a self-centering alignment system (SCAS) can be used as a template for electroforming a nickel mould insert. This mould insert is subsequently used as a shim for the replication of the SCAS by means of hot embossing. Successful replication was achieved in PMMA. The SCAS replicas were geometrically characterized and were shown to be slightly out of spec, mainly due to shrinkage. The root-mean square surface roughness ($R_q$) was measured for the inner sidewalls and the top side of the replicas. As expected, low surface roughnesses were measured ($R_q=48-62$ nm), which facilitates the demoulding process as well as the fiber insertion in the resulting replicas. Hot embossed replicas inherently possess a residual layer underneath the replicated structure which needs to be removed to achieve through-holes in the SCAS to allow for fiber insertion into the structure. A suitable method for removing the residual layer is currently being developed. Once the residual layer can successfully be removed, we will proceed with the assembly and testing of single-mode fiber connectors based on hot embossed SCAS replicas.

Acknowledgments

This work was supported by the Agency for Innovation by Science and Technology Flanders (IWT) under contract 095115 (EP2CON), and in part by the EU FP7 project VECTOR (Grant agreement no. 318247), BELSPO-IAP Photonics@be, the Methusalem and Hercules foundations, the IOF, Flanders Make and the OZR of the Vrije Universiteit Brussel. Further support was obtained from the Karlsruhe Nano and Micro Facility (KNMF, www.kit.edu/knmf), a Helmholtz Research Infrastructure at Karlsruhe Institute of Technology.

References

REFERENCES


