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Published in:
Opt Eng

DOI:
10.1117/1.OE.55.7.076112

Publication date:
2016

Citation for published version (APA):

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Download date: 11. Aug. 2021
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Abstract. This paper presents the hot-embossing replication of self-centering fiber alignment structures for high-precision, single-mode optical fiber connectors. To this end, a metal mold insert was fabricated by electroforming a polymer prototype patterned by means of deep proton writing (DPW). To achieve through-hole structures, we developed a postembossing process step to remove the residual layer inherently present in hot-embossed structures. The geometrical characteristics of the hot-embossed replicas are compared, before and after removal of the residual layer, with the DPW prototypes. Initial measurements on the optical performance of the replicas are performed. The successful replication of these components paves the way toward low-cost mass replication of DPW-fabricated prototypes in a variety of high-tech plastics. © 2016 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: 10.1117/1.OE.55.7.076112]

Keywords: alignment structures; deep proton writing; electroforming; fiber connector; hot embossing; micromilling; mold insert; poly-mer replication; precision alignment.

Paper 160808P received May 24, 2016; accepted for publication Jul. 7, 2016; published online Jul. 22, 2016.

1 Introduction

The relentlessly increasing demand for bandwidth, mainly driven by cloud-based services and (ultra-)high-definition video-on-demand services, pushes the need for high-bitrate Internet connections. The only future-proof solution for such high-speed networks is to use optical fiber and bring it as close as possible to the end user—ultimately, into the subscriber’s home.1–3 To deploy “fiber to the home” on a massive scale, there is a strong need for robust and easy-to-use, but at the same time high-performance, fiber connectivity solutions. These solutions must allow for physical mating of single-mode fibers with very low loss, or in other words, with submicrometer alignment accuracy. To this end, we have designed a self-centering alignment system (SCAS), which centers a fiber upon insertion to ensure a good lateral alignment accuracy between two mated single-mode fibers.4,5 This SCAS is based on deflectable microsprings that exert a force on the fiber while it is being inserted.6,7 The advantage of self-centering fiber connectors is that they can mitigate the effect of the fabrication tolerance (of typically ±0.7 μm and up to ±1.0 μm8) 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.9 We have recently shown that an insertion loss down to 0.1 dB can be achieved with connector assemblies based on prototype SCAS components fabricated through deep proton writing (DPW).5 Given the very high number of fiber connections that need to be installed when rolling out a fiber-to-the-home network, it is imperative that those components can be made at low cost and in high volumes. In addition, the components should be compatible with stringent environmental conditions, such as an operating temperature ranging from −40°C to 70°C.10 This means that the parts should be fabricated of high-performance plastics with replication technologies such as microinjection molding or hot embossing.11 Therefore, we also show the replication of the components in polysulfone (PSU) after initial testing with polymethylmethacrylate (PMMA). Other high-performance materials, such as polyetherimide (PEI), could be considered as well. The design of a three-spring SCAS is shown in Fig. 1(a).

Notice that the central opening is 121 μm in diameter, which is smaller than the nominal cladding diameter of a G.652 SMF (i.e., 125 μm). 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. To be able to prove the concept of the SCAS and assemble and connect prototype SCAS connectors, two 700-μm diameter holes are included to accommodate mechanical transfer (MT-) pins.12 These pins are high-tolerance alignment pins which are used in commercial fiber connectors such as the multiple push-on (MPO) and mechanical transfer registered jack (MT-RJ) connectors.12,13 We have chosen to make our proof-of-concept SCAS compatible with MPO connectors, as defined in the Fiber Optic Connector Intermateability Standard (FOCIS) TIA-604-5. It is clear that adding MT-pins for alignment introduces another alignment tolerance and reduces the value of self-centering. Note that our ultimate goal is to create a ferruleless connector in which two fibers would meet in an adaptor containing multiple SCASs, thus moving past the misalignment caused by the...
fabrication tolerances on both the alignment ferrules and the fiber. The aspect ratio of the SCAS is 5:1 (500-μm deep and 100-μm wide cavities). In this paper, we discuss the use of hot embossing for the replication of SCAS components. In Sec. 2, we describe the DPW technology that was used for prototyping the master component in PMMA. We also discuss the justified partial metalization of that master component in order to realize a metal mold insert through electroforming. Finally, we discuss the hot-embossing replication of these structures in PMMA and PSU and the adapted micromilling process we developed to remove the residual layer inherently present in the hot-embossed replicas. In Sec. 3, we describe the results of the hot embossing and residual layer removal and characterize the geometrical dimensions of the replicas with the master component fabricated through DPW. Last but not least, we perform optical insertion loss measurements of fiber connector assemblies making use of the fabricated replicas.

2 Technology Description and Experimental Methods

2.1 Prototyping by Deep Proton Writing

DPW is a rapid prototyping technology for micro-optical and micromechanical components. DPW finds its origins in the LIGA technology (Lithographie, Galvanoformung, Abformung), but uses protons rather than x-rays for the irradiation process. In addition, 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-μm thick nickel plates with apertures ranging from 50 to 300 μm. This allows to work with proton energies of up to 16.5 MeV, which enables irradiation of PMMA samples that are up to 2-mm thick. The concept of DPW is based on the fact that irradiating high-molecular-weight PMMA \( (M_w \approx 10^6 \text{ g/mol}) \) with high-energy protons will break the long polymer chains. This will cause the physical and chemical material properties in the irradiated zones to be very different from those in the unexposed bulk material. This will, in turn, allow the irradiated zones to be selectively etched away in so-called GG developer (which consists of 60% diethylene glycol monobutyl ether, 20% morpholine, 5% 2-aminoethanol, and 15% de-ionized water) during 105 min at 38°C while using an ultrasonic stirrer. This way, DPW enables high-quality prototyping of (arrays of) microholes, micropillars, and micromirrors with optical quality sidewalls. An important characteristic of DPW is that the protons scatter within the sample material during irradiation, causing a slightly conical shape when irradiating microholes. In this case, the conical shape is an asset, since it both facilitates the fiber insertion in the SCAS (by avoiding perfectly vertical and flat sidewalls) and the demolding 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 μm, 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-μm wide, the resulting aspect ratio is 5:1. This component was irradiated using the smallest available proton beam, with a diameter of 50 μm, to be able to pattern the fine features of the central hole region in the SCAS. The proton fluence was optimized to \( 5.2 \times 10^8 \) protons/μm² to achieve the desired dimensional shape. The total irradiation time for two 700-μm diameter alignment holes and the SCAS is about 5 h. Hence, it is clear that DPW is a costly and time-consuming process, ideally suited for rapid prototyping but not for large-volume production. Note that self-centering optical fiber holders, created by combining proton beam writing and symmetric swelling of PMMA, have previously been reported. This approach requires the diffusion of a monomer into a DPW-irradiated PMMA sample while a fiber is inserted into the irradiated and partly etched microholes. It is clear that this technique is not at all scalable to large-scale production.

2.2 Mold Insert Formation

Although DPW is not a mass replication technique as such, one of the assets of DPW is that once the master component has been prototyped, a metal mold can be generated from the master by applying a combination of joining technology and
electroforming. Electroforming of PMMA master components has been known for a long time, and we have previously shown the successful application of this method for the replication of DPW-prototyped micromirror structures. However, as opposed to the latter components, 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 those errors, we have developed a justified partial metallization process for the mold formation. This process requires the DPW prototype to be attached to a copper substrate. To avoid excessive amounts of adhesive in the small through-holes, a dip method was used to apply adhesive to the prototype structure. Even with this special dip method, some adhesive covered the copper substrate in the smallest features, leading to an undesired "rounding" effect as illustrated in the scanning electron microscope (SEM) image of the mold insert in Fig. 2(a). To minimize this effect, 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 covers the rest of the structure only after filling those through-holes, a seed layer is deposited on the structure with physical vapor deposition through a mask. This allows us to avoid defects like void spaces or loose parts in the electroformed nickel mold. The final step of the mold insert fabrication consists of cutting the mold insert to its desired dimensions by wire electron discharge machine cutting.

2.3 Replication by Hot Embossing

The mold insert is inserted in the upper part of our hot-embossing equipment (a HEX03 from Jenoptik Mikrotechnik GmbH). The lower part of the hot embosser consists of a demolding plate with a high surface roughness (sandblasted stainless steel) to facilitate the demolding of replicas. Both the upper and lower parts can be heated up to 280°C and can maintain a pressure of up to 200 kN. The materials considered for the self-centering alignment structure replicas are PSU and PMMA. PMMA is selected because of our previous experience with this material for hot embossing as well as to enable a comparison between the DPW prototype and its replicas in the same material. PSU is a polymer, which is commonly used for microhot embossing and shows a high resistance to creep and is compatible with the stringent environmental conditions discussed in Sec. 1. The embossing process begins with placing a 20 × 20 × 2 mm³ piece of PMMA or PSU on the demolding plate. Then the upper and lower parts of the embosser close and form a vacuum chamber which is evacuated to a pressure below 100 mbar. The mold insert and demolding plate are subsequently heated up to 180°C or 235°C for the replication in, respectively, PMMA or PSU. Once this temperature is reached the actual embossing happens with a force of 50 kN, which is maintained for 5 min. Then the system is cooled down to 80°C while holding the force at 50 kN in order to minimize the effect of shrinkage of the polymer and to prevent 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 demolding plate because the friction of the replica with the sand-blasted demolding plate is larger than the friction with the mold insert. The total cycle time for an SCAS component to be replicated is about 30 min. An SEM image of a silver-plated PMMA replica can be seen in Fig. 2(b).

2.4 Residual Layer Removal

Replicas made by standard hot embossing inherently possess a residual layer underneath the desired component as can be seen in Fig. 3. This is not problematic and can even be an asset for part handling (it can indeed serve as replica holder/magazine) in the case that no through-holes are required. In our case, however, a fiber should be able to penetrate through the replicated components and the cantilever springs should be able to deflect. Hence, the residual layer should be removed. Several approaches have been reported to avoid the formation of a residual layer during replication or to remove it where desired. Heckele et al. showed the fabrication of through-holes by hot embossing of a multilayer stack consisting of different polymers. Rapp et al. used a double-sided hot-embossing process in which a PSU secondary mold was used to make through-holes in PMMA. Zhu and Cui used an aluminum alloy buffer layer in a combination of a hot-embossing process with an indentation process. All these approaches require the use of multiple materials, which increases the complexity and cost of the

Fig. 2 SEM pictures of (a) the mold insert and (b) a silver-plated PMMA replica.
hot-embossing process. We present an alternative approach to remove the residual layer through a post-embossing processing step consisting of a combination of silicone molding\textsuperscript{30} and conventional micromilling. For visual identification, we first mark the residual layer directly around the replica and then cut the residual layer down to a small size (of \(\sim 15 \, mm \times 20 \, mm\)) in order to increase the amount of replicas we can process simultaneously. It is also possible that multiple SCAS structures are included in a single mold insert, which would allow for multiple replicas to be molded at the same time, sharing the same residual layer. Replicas are then placed bottom-down on a flat reference plate and subsequently embedded into a liquid silicone, which is a mixture of a rubber (10 parts by weight) and a catalyst (1 part by weight). The silicone rubber (Rhodorsil RTV 246A) contains approximately 90\% (by weight) methyl-vinyl-polysiloxane, <1\% hexamethyldisilazane, 9\% amorphous silica, and <0.5\% modified chloroplatinic acid. The silicone catalyst (MCP-HEK CAT750) is a hydride-terminated polydimethyl-siloxane. When cutting down the size of the residual layer around each replica, care needs to be taken to maintain enough residual layer surface. This allows the liquid silicone rubber to apply sufficient pressure to push the replica down against the flat reference plate. If not, the replica could be embedded in the silicone under an angle, which could severely impede the subsequent residual layer removal process. In cases where multiple replicas are included on a single residual layer, this is not an issue. The CAT750 catalyst ensures hardening of the silicone over a period of 24 h after mixing with the silicone rubber. Some silicone flows under the edges of the residual layer. When removing the flat reference plate, the residual layer’s bottom side is thus partially submerged in silicone rubber and partially free, as can be seen in Fig. 4(a) for a hot-embossed replica of an SCAS with outer dimensions of 2.5 mm \(\times\) 6.4 mm. After hardening, the silicone rubber mold can be mounted on a conventional micromilling machine (a VHF CAM 100 in our case), which we have equipped with a Volpi AS 11/50 video microprobe and CCD-camera for visual alignment of the structure with respect to the milling tool. The residual layer is milled away with a step-wise approach. A double-tooth cutter with fishtail of 3-mm diameter is used at 8000 rpm with a cutting speed of 0.3 mm/s. Starting with a manual touch-down of the milling tool, 10 \(\mu m\) is milled away from the residual layer each step, until the residual layer of the SCAS is fully removed. The reason we choose to take steps of 10 \(\mu m\) is that this is our micromilling machine’s resolution. As can be seen in Fig. 4(b), the replica is now free of residual layer once the marked zone around the SCAS is milled away. A microscope image of the surface after micromilling can be seen in Fig. 5(b). After optimization of this method, we were able to successfully remove the residual layer of the SCAS replicas with a yield higher than 80\% for both the PMMA and PSU replicas. The reason for failures is the deformation of the residual layer of certain replicas during demolding. This deformation can manifest itself as a bending of the edge of the residual layer as depicted in Fig. 6(a). This can lead to the sample being mounted under an angle in the micromilling machine as mentioned earlier. The deformation can also manifest itself in the center of the residual layer, where the SCAS is located, as depicted in Fig. 6(b). In this case, the visual feedback method (i.e., the marked zone being milled away, as shown in Fig. 4(b)), will not be adequate to accurately determine when the residual layer is removed. This gives rise to the operator of the micromilling machine to either remove too little of the residual layer or to continue milling after the SCAS has been removed. Either one of the above-described cases or a combination can lead to damaged microsprings in the SCAS and thus unusable components.

3 Results

3.1 Geometrical Characterization

The mold inserts fabricated by electroforming DPW prototypes (described in Sec. 2.2) and the replicas made from these mold inserts by hot embossing (described in Sec. 2.3) are measured using a Werth UA-400 multisensor coordinate measure machine (CMM). For the geometrical characterization, we focus on measuring two critical features of the SCAS: the diameter of the central opening and of the MT-pin holes as indicated in Fig. 1(a). When the central opening becomes larger than 126 \(\mu m\) in diameter, the structure will no longer exhibit any self-centering functionality since the cladding diameter of a G.652 SMF is 125 \(\pm\) 1 \(\mu m\) as mentioned earlier. 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 to 124 \(\mu m\) 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. To optimize the electroforming process, six DPW prototypes were selected, based on their dimensions, to use for creating mold inserts. The results of the final two electroformed mold inserts are shown in Table 1. Since one mold insert was damaged during the optimization of the hot-embossing process for the replication of components in PSU, there is no geometrical data available on that insert. (The electroformed mold insert was not measured prior to replication tests because the CMM measurements took place at a different location than the electroforming and hot embossing.)

Regarding the central hole, the second mold insert is in spec (i.e., inside the 121- to 124-\(\mu m\) range\textsuperscript{31}). For the MT-pin hole though, it is slightly out of spec (i.e., outside

![Fig. 3 A hot-embossed SCAS replica in PMMA with residual layer cut down to size (\(\sim 15 \, mm \times 20 \, mm\)) for residual layer removal.](image-url)
In Fig. 2(a), we can see that the mold inserts show rounded features as mentioned earlier, caused by an excess of adhesive that we were unable to remove with laser ablation. This will cause the SCAS replicas' spring cavities [shown in Figs. 2(b) and 5(b)] to be incompletely 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 rounding could be improved by further optimizing the laser ablation process or by using a clamping approach instead of adhesive bonding during mold fabrication. Considering the replicas, we can see that both the central hole and MT-pin hole are slightly out of spec (i.e., outside the 119 to 124 and 699- to 701-μm range12). The data show that the hot embossing replication process is better optimized for PMMA than it is for PSU since the dimensions of the PMMA replicas are closer to the design target and the standard deviation on the central hole diameter is smaller. After removal of the residual layer, the average value of the central hole and MT-pin hole diameter becomes smaller. This is possibly because the microsprings can deform slightly while the material shrinks after hot embossing and relax after the residual layer is removed. Since the standard deviations vary; however, no definite conclusion can be drawn for the effect of the residual layer removal on the dimensions of the SCAS. From the data of the second mold insert (see Table 1), we can also estimate the shrinkage of the PMMA replicas fabricated with this mold 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 microstructures, which can affect the total resulting shrinkage behavior. Note that it is possible to compensate for the shrinkage by modifying the design of the DPW prototypes. This way the mold 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 mold will shrink to their target dimensions after the hot-embossing replication.

3.2 Surface Roughness Measurements

Next to the dimensional characterization, we also evaluate the surface roughness of the replicas, since it has a large influence on the demolding step of the hot-embossing process and on the fiber insertion into the resulting replicas. The sidewall, top, and bottom sides of the replicas were measured using a Bruker Contour GT-I noncontact optical profiler. The roughness on the bottom side results directly from the micromilling process used for the removal of the residual layer. On the other hand, the roughness of the top side and inner sidewalls is a result of the electroformed mold’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 lower surface roughness than the micromilled bottom side. The root-mean-square surface roughness, defined as $R_q = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \frac{1}{n} \sum_{i=1}^{n} y_i^2}$ (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 $\mu$m × 47.8 $\mu$m was determined and averaged per replica under investigation. Four replicas in PSU and PMMA were investigated for top- and bottom side surface roughness. Two PMMA and one PSU replica were cut open by micromilling to investigate the inner sidewall surface roughness. The results are shown in Table 2 and from this data we can deduce that the milling parameters for the residual layer removal are better optimized for PMMA, since smoother bottom surfaces are obtained. This can be explained by the fact that PMMA is less elastic (i.e., has a higher Young’s modulus) than PSU. As expected we can confirm that the top side and inner sidewall surface roughness is lower than that of the micromilled bottom side and that the measured surface roughness for the top side and inner sidewalls are very similar for PSU and PMMA replicas. In particular, the low sidewall roughness is beneficial, not only for the demolding of replicas (since the sidewalls cause the most friction with the mold insert during demolding), but also for having minimal friction during fiber insertion in the replicas during connector assembly.

3.3 Insertion Loss Measurements

As mentioned in Sec. 1, the final goal of replicating SCAS structures is to use them for high-precision alignment of two SMFs in order to create a low-loss, high-performance, physical-contact fiber connection. We have recently shown that an insertion loss down to 0.1 dB (and hence a grade B optical performance) can be achieved for a connector assembly made with DPW prototypes. Here, we characterize the performance of self-centering connector assemblies based on replicated components, where we use the connection between two commercial MPO connectors (which typically have 0.2 dB insertion loss) as reference, as shown in Fig. 7(c). Since the SCAS only ensures a good lateral alignment between two SMFs, a prealignment plate is included in the assembly at a distance of 4 mm from the SCAS to limit the angular misalignment to ~0.9 deg, as can be seen in Fig. 7(a). To make sure the axial misalignment is reduced to a minimum, a custom-made broad spectrum interferometer was used to align the SMF’s facet with the front-side of the alignment structure, with an accuracy of 2.5 $\mu$m. After this, the fiber is fixated by means of UV exposure of UV-curable adhesive applied on the prealignment structure. Three different SCAS assemblies were connected with an MPO connector as shown in Fig. 7(b). Note that commercially available MPO-connectors are angled physical contact connectors, which means that their facet is polished under an angle.

<table>
<thead>
<tr>
<th>Mold insert</th>
<th>Central $\varnothing$ (µm)</th>
<th>MT $\varnothing$ (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DPW prototype</td>
<td>121.3</td>
<td>701.2</td>
</tr>
<tr>
<td>Mold insert</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>PMMA replicas (5)</td>
<td>122.7 ± 2.4</td>
<td>720.7 ± 5.6</td>
</tr>
<tr>
<td>PMMA replicas milled (5)</td>
<td>121.6 ± 4.2</td>
<td>707.7 ± 4.1</td>
</tr>
<tr>
<td>PSU replicas (5)</td>
<td>126.4 ± 5.6</td>
<td>711.0 ± 4.2</td>
</tr>
<tr>
<td>PSU replicas milled (2)</td>
<td>124.8 ± 9.4</td>
<td>709.8 ± 1.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mold insert 2</th>
<th>Central $\varnothing$ (µm)</th>
<th>MT $\varnothing$ (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>120.5</td>
<td>701.5</td>
<td></td>
</tr>
<tr>
<td>122.9</td>
<td>700.2</td>
<td></td>
</tr>
<tr>
<td>128.3 ± 2.8</td>
<td>713.0 ± 10.7</td>
<td></td>
</tr>
<tr>
<td>127.2 ± 1.8</td>
<td>710.9 ± 13.7</td>
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Table 2 Measured root-mean square surface roughness ($R_q$) averaged over three randomly selected areas of 63.7 $\mu$m × 47.8 $\mu$m of hot embossed SCAS replicas made with mold insert 1. The number of measured samples is mentioned in brackets.
8 deg angle. Hence, we had to polish the MPO ferrules perpendicularly such that a physical connection could be made with flat-cleaved fibers. The smallest insertion loss was measured to be 0.84 dB when connecting an SCAS connector assembly from a PMMA replica to a perpendicularly polished MPO connector, as shown in Fig. 7(d). Considering the nonideal rounded features in the mold insert [Fig. 2(a)] and in the resulting replicas [Fig. 5(b)] and the fact that we currently have not compensated the prototypes for shrinking. These results show that our connector assemblies using the replicated self-centering alignment structures have the potential to be as performant as current state-of-the-art optical single-mode fiber connectors, taking into account that we have already demonstrated insertion losses down to 0.1 dB with the DPW prototypes. To realize this potential, further optimization of the prototype (e.g., compensating for the shrinkage), of the mold formation and of the replication process is needed.

4 Conclusions
We have shown that a DPW fabricated PMMA prototype of an SCAS can be used as a template for electroforming a nickel mold insert. This mold insert is subsequently used as a shim for the replication of the SCAS by means of hot embossing. Successful replication was achieved in two materials: PMMA and PSU. Hot embossed replicas inherently posses 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. We developed a method in which we remove the residual layer by micromilling in steps of 10 μm after encasing the SCAS replica in a silicone rubber with the aim of holding the small SCAS components in place during the micromilling process. With this method, a yield better than 80% was achieved for residual layer removal. 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, top and bottom sides of the replicas. As expected, the bottom side (i.e., the micromilled side) showed the highest surface roughness ($R_q = 240$ to 390 nm) while lower values were measured for the inner sidewalls and top side ($R_q = 48$ to 62 nm), which facilitates the demolding process as well as the fiber insertion in the resulting replicas. Finally, the SCAS replicas were used to create MPO-compatible single-mode fiber connector assemblies and an insertion loss of 0.84 dB was achieved compared to an MPO–MPO reference connection. The rounded features in the mold insert and the fact that we did not compensate for shrinkage, leads to the replicas being slightly out of spec. For this reason, environmental testing of the replicas has not been performed yet. However, taking into account the insertion loss of 0.1 dB obtained with SCAS prototypes, this result shows that the replicated SCAS has the potential to perform as well as state-of-the-art connectors after further optimization of the prototype (e.g., compensation for shrinkage), of the mold formation and of the replication process. Indeed, while, in this paper, we used an MPO-compatible layout to be able to perform a proof-of-concept demonstration, our ultimate goal is to move toward ferruleless connectors to fully exploit the potential of the SCAS, improving the

![Fig. 7 SCAS assembly with the prealignment plate in green, spacer in gray, SCAS in red, MT-pins in yellow, and the single-mode fiber in black. (a) This assembly (male) can be aligned with another assembly (female) by inserting the MT-pins in the other assembly and pressing them together such that physical contact is made. (b) A connection between an SCAS assembly and a perpendicularly polished MPO ferrule. Schematic representation of (c) the reference measurement between 2 MPO connectors and (d) the insertion loss measurement between an MPO connector and an SCAS connector assembly.](image)
alignment accuracy and thus the optical performance even further.

Acknowledgments
VUB is a member of Flanders Make. 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 and the OZR of the Vrije Universiteit Brussel. Further support was obtained from the Karlsruhe Nano and Micro Facility (www.kit.edu/knmf), a Helmholtz Research Infrastructure at Karlsruhe Institute of Technology.

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