Fabrication of Microgrooves with Excimer Laser Ablation Techniques for Plastic Optical Fibre Array Alignment Purposes.

Kris Naessens, An Van Hove, Thierry Coosemans, Steven Verstuyft, Heidi Ottevaere[*], Luc Vanwassenhove, Peter Van Daele and Roel Baets.
Universiteit Gent / IMEC – Dept. of Information Technology (INTEC)
Sint-Pietersnieuwstraat 41, B-9000 Gent, Belgium.
Tel: +32-9-264-3316, fax: +32-9-264-3593, e-mail: kris.naessens@intec.rug.ac.be.

[*]Vrije Universiteit Brussel, Lab for Photonics, Dept. of Applied Physics and Photonics (TW-TONA)
Pleinlaan 2, B-1050 Brussel, Belgium.

ABSTRACT.

Laser ablation is extremely well suited for rapid prototyping and proves to be a versatile technique delivering high accuracy dimensioning and repeatability of features in a wide diversity of materials. In this paper, we present laser ablation as a fabrication method for micro machining of arrays consisting of precisely dimensioned U-grooves in dedicated polycarbonate and polymethylmetacrylate plates. The dependency of the performance on various parameters (wavelength, energy density and pulse frequency) is discussed. The fabricated plates are used to hold optical fibres by means of a UV-curable adhesive. Stacking and glueing of the plates allows the assembly of a 2D connector of plastic optical fibres for short distance optical interconnects.

Keywords: Excimer laser ablation, optical alignment, optical interconnect, plastic optical fibre.

1. INTRODUCTION.

A number of technologies are at our disposal for fabrication of microstructures: LIGA (German acronym for lithography, electroforming and molding), deep proton lithography and standard processes from the micro-electronic manufacturing technology. In general these fabrication methods suffer from low throughput, severe environmental requirements and high cost. Injection molding and embossing allow mass fabrication in a very fast way but due to expensive master tools (matrix), these technologies are unsuitable for fabrication of components in small or moderate amounts.

The last decade, excimer laser ablation has acquired the reputation of being a reliable technology for fabrication of microstructures. This non-resist technique does not require clean-room facilities, can be applied on a broad range of materials and is potentially fast since it allows parallel processing by means of mask patterns. It is therefore extremely suited for prototyping, proof-of-principle and fabrication of micro parts in small amounts. Typical applications for laser ablation are via-drilling in printed circuit boards, removal of short cuts in electronic circuitry, wire stripping, fabrication of waveguides, micro-lenses and alignment structures in polymers[1,2,3,4,5]… In this paper we focus our attention on the latter and investigate the feasibility of the technique for optical interconnect applications. For short-distance purposes as e.g. chip to chip interconnect within racks, POF (Plastic Optical Fibre) can be a very valuable alternative for glass fibre based solutions. Due to its higher numerical aperture and core size in comparison to glass fibre, POF provides enhanced coupling efficiency, and relaxed alignment tolerances. In addition, the fibre is very flexible, allows easy end-facet preparation and is a basically low cost solution. However, at this moment only 1D connectors (MT-like ferrules) are commercially available while the ever-increasing need for higher bandwidth begs for 2D solutions. In this paper we demonstrate the fabrication of such a connector with laser ablation and report on our first results. FIG. 1 illustrates the concept of this 2D connector. It consists of a number of stacked polymer plates (thickness slightly smaller than 250 micron) with U-grooves in which POFs are fixed at a pitch of 250 micron.

We chose a trench geometry as surface profile for plastic optical fibre alignment since the open upper side allows rather easy insertion of the fibre and the depth of the grooves, defined by the diameter of the fibres (125 micron), is within the limits of what one can achieve with excimer laser ablation by aperture or mask imaging.

The connector can be used for coupling light from a 2D array of RCLEDs into fibres by providing alignment features (e.g. pinholes) on the front side.

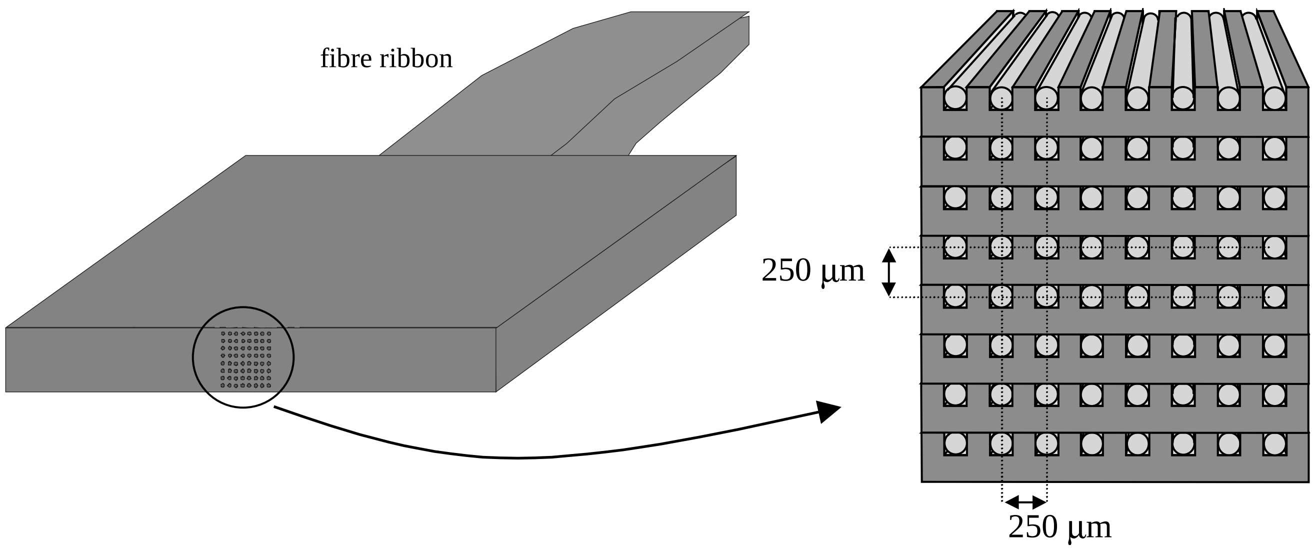


FIG. 1. The 2D connector concept for plastic optical fibres.

2. FABRICATION OF THE GROOVE ARRAY IN POLYMER PLATES.

For fabrication of grooves, we investigated two different kind of polymers, PMMA (PolyMethylMethAcrylate) and PC (Polycarbonate) as well as two excimer-laser source wavelengths: 248 nm (KrF) and 193 nm (ArF). PMMA has a rather low absorption coefficient (2000 cm^{-1} and 200 cm^{-1} at 193 and 248 nm[7] respectively) which allows the pulse to penetrate deeper into the material (higher ablation rate) but which is also responsible for the higher threshold of the pulse intensity.

We applied two different methods (both common in micro machining) which we will call moving-aperture and mask method. The first implies the use of a suitable single aperture which is imaged onto a substrate that is translated slowly between two or more pulses. The latter involves the imaging of a more complex mask pattern. Depending on the pattern size, scanning might not be necessary anymore, although it may be beneficial to the resulting ablation quality of the trenches: by partially overlapping pulses (slow translation of the substrate), one averages depth variations of the ablated surface due to spatial inhomogeneity of the laser beam. This is only possible when the ablated geometry is translation invariant (e.g. a groove). We will call the combination of scanning and mask projection the hybrid mask method.

After ablation of the grooves, a cleaning step with water and pressurized air is necessary to remove debris (macroscopic particles which did not vaporize and remained in or close to the ablated region) on the polymer surface.

The experiments were carried out with a Lumonics Pulse Master 848 (suitable for both KrF and ArF gas mixtures) and by means of an optical set-up as in FIG. 2. A Molectron J3 pyroelectric joulemeter, put at far distance from the image plane, was used for the energy density measurements after the substrate was removed from the beam path.

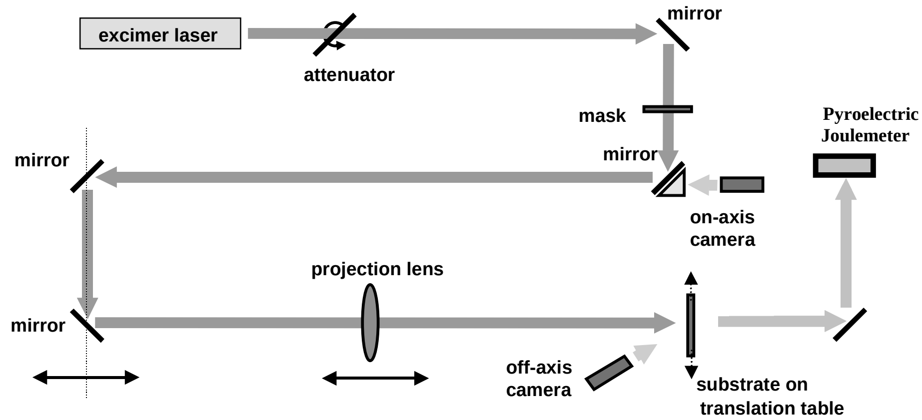


FIG. 2. Laser ablation set-up.

FIG. 3 and TABLE 1 illustrate the results. Both arrays consist of 8 grooves of 126 micron depth and 9 mm length with a pitch of 250 micron. The width has been optimized for carrying an optical plastic fibre taking the finite steepness of the trench into account. Fabrication time for the structure in polycarbonate with the moving aperture method (on the left) is approximately 11 hours while the one on the right (the same array in PMMA with the mask method) takes only 18 minutes. The mask pattern consists of 4 grooves of length 2.5 mm (500 micron on substrate level, taking an imaging from mask to sample with demagnification 5 into account) and is limited in size by the aperture of the projection lens. It consists of a quartz substrate (transparent for both excimer wavelengths) on which a metal pattern has been deposited. The maximum allowed energy density is about 100 mJ/cm^2. Note that a mask with the full array geometry would result in a fabrication time of only a few minutes.
A number of parameters are at our disposal for ablating this structure: on-substrate energy density and pulse frequency. Both illustrated structures were fabricated at a low pulse frequency (10-15 Hz) and energy (lower than 200 mJ/cm^2). Although increasing each or both parameters speeds up the process, this is not very beneficial to the quality of the structure (roughness and morphology of the groove bottom): at high frequencies and energies we observed the creation of large macroscopic particles at the bottom (several microns to tens of microns) which cannot be removed anymore, and a brown-like colour shift of the polymer which suggests that the remaining material has been thermally damaged. Ablation at 248 nm seems more sensitive to this phenomenon in comparison to the ArF wavelength.
The ablated trench does not have vertical walls due to the imaging principle of an aperture or mask. However, the steepness of the latter can be controlled to a certain extent by the pulse energy density: we observed angles as low as 69 (low pulse intensity) up to almost 81 degrees (high energy densities).

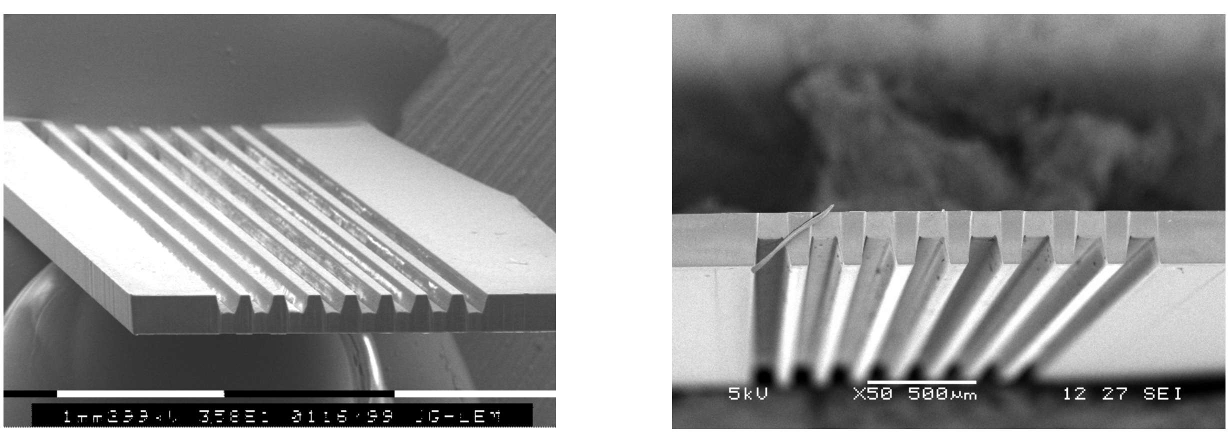


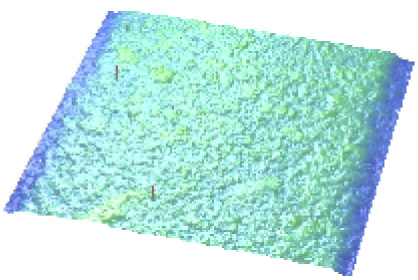
FIG. 3. Array fabricated with moving aperture method in PC at 248 nm (left), array with hybrid mask method in PMMA at 193 nm.

The grooves were not ablated to full depth at one go. Experiments pointed out that a process in two or more steps allows faster ablation and smoother structures than when ablated at once. This can be explained by the steepness of the exposed surface which undergoes ablation: in the first case this angle is much smaller than in the latter. Thus the energy density at this surface remains higher and ablation still takes place without much loss of speed.
Finally the experiments indicated that from an ablation speed and surface morphology point of view, PMMA ablates better at 193 nm (FIG. 4) while PC performs better at 248 nm.

	moving aperture method at 248 nm in PC	**hybrid mask method at 193 nm in PMMA**
on-substrate energy density	≈178 mJ/cm^2	160 mJ/cm^2
pulse frequency	10 Hz	15 Hz
steepness	72 degrees	78 degrees
number of pulses per spot	282×3	224×2
ablation speed	≈150 nm/pulse	≈280 nm/pulse
RMS roughness	0.40 μm	0.33 μm
fabrication time	11 hours	18 minutes

TABLE 1. Ablation parameters and experimental results.

The final step in fabrication of the groove plate involves laser cutting of the plate end faces. Since vertical walls are required on the connector side, we used a contact mask in combination with a higher energy density and pulse frequency instead of a projection mask. It basically consists of a semiconductor plate (Si or GaAs) with a very flat facet on one side. A translation stage puts the mask at the desired position above the trenches and then brings it in direct contact with the grooved plate. A 500×500 μm laser beam scans along the mask facet and fires higher energy pulses at 50 Hz, producing a rather smooth vertical cut in the polymer substrate (front side of the plate in FIG. 3 and 4, right).



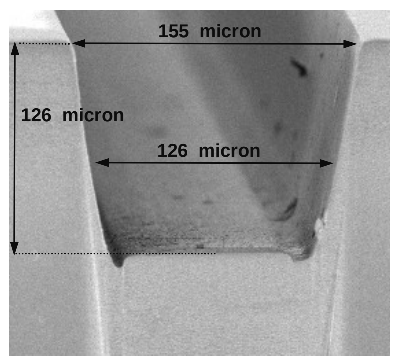


FIG. 4. Surface scan (WYKO) of the groove bottom (left) and a close-up on the groove profile (SEM, right).

3. ALIGNMENT AND FIXING OF PLASTIC OPTICAL FIBRES.

Aligning the fibres in the grooves is performed by means of the ribbonisation set-up in FIG. 5: an array of POFs is tightened while the intermediate stage carrying the polymer plate(s), is translated upwards (Z direction). In this way the fibres are gradually introduced in the grooves by slightly adjusting the position of the substrate in the X, Y directions.
Fixation of the fibres is achieved with a UV-curable adhesive which is flown in the grooves and exposed to a UV-source afterwards. By cutting the fibres one by one along the front side of the plate with the hot knife technique (110 °C), one achieves very smooth fibre facets due to a simultaneous cutting and melting process. The polymer plates are now ready to be stacked.

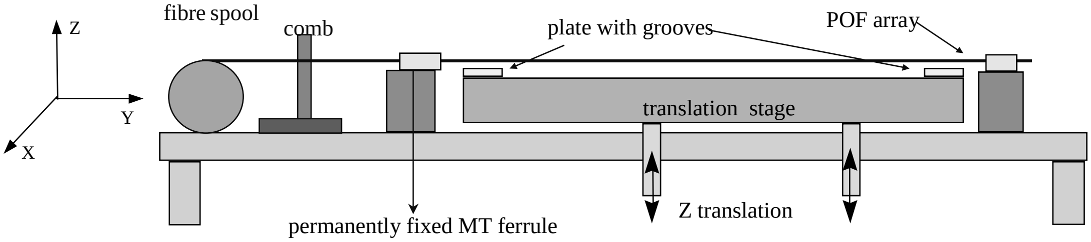


FIG. 5. The ribbonisation set-up.

4. ASSEMBLY OF A 2D CONNECTOR.

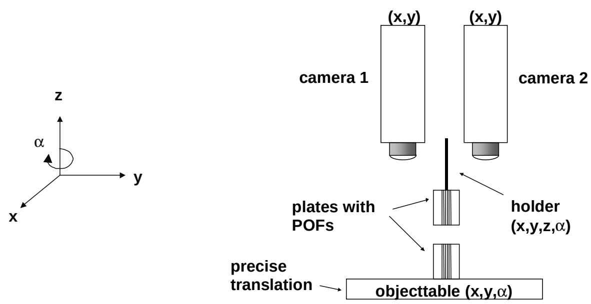


FIG. 6. The 'virtual alignment' set-up.

Accurate stacking of the POF carrying plates is performed with the set-up illustrated in FIG. 6 ('virtual alignment'). By means of two cameras (both with crosshairs alignment features on-screen) and a high precision translation and rotation table the first plate is aligned with the crosshairs (the exact procedure is explained schematically in FIG. 7). After this first substrate is moved over 250 micron the other plate is positioned and aligned along the crosshair pattern. The final step in the stacking process involves glueing the substrates together with an UV-curable adhesive. This procedure can be repeated for every other groove plate. The procedure does not require dedicated alignment features to be put on the plates themselves or fabrication of any mastertool. However it is only suitable at prototyping level since the method is rather time consuming.

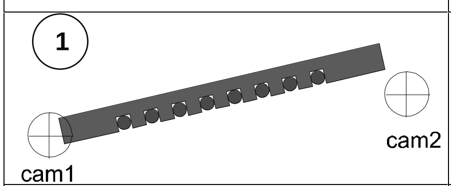
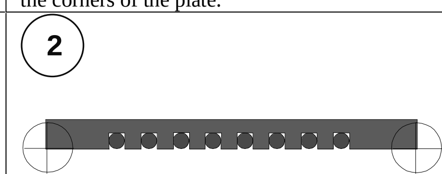
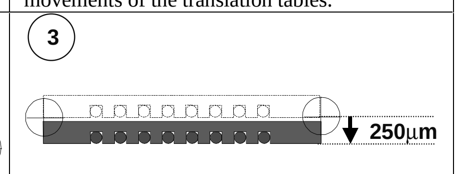
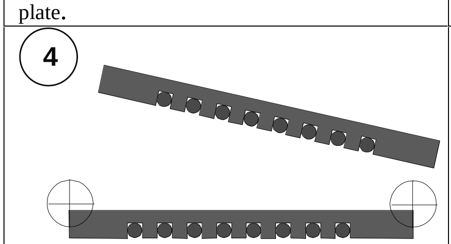
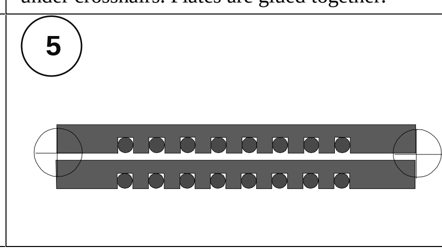
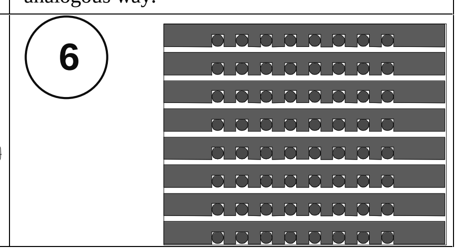
1. The first plate is looked at with two moveable cameras	2. The plate is rotated until its edges are parallel with the crosshairs. Cameras are positioned on the corners of the plate.	3. The plate is moved over an exact distance of 250mm. Lines of the crosshairs are parallel with movements of the translation tables.
		
4. The second plate is brought in vicinity of first plate.	5. The corners of second plate are positioned under crosshairs. Plates are glued together.	6. The other plates are positioned in an analogous way.
		

FIG. 7. The 'virtual alignment' procedure.

5. EXPERIMENTAL RESULTS.

We report here the results on a 2×8 POF ferrule. The exact position of the fibres was determined by coupling light into the loose ends and scan the connector facet with a suitable detector in proximity of the latter. The table underneath represents the accuracies we achieved with our first test plates. For both directions (X,Y) we measured the average value, and the standard deviation of the position of one fibre core towards the adjacent fibre cores. The values of x and y represent the spacing between two adjacent fibre cores in the horizontal and vertical direction respectively (ideal value is 250 micron); Δx and Δy indicate the deviation in position of fibre cores from their ideal position towards the neighbouring fibre in the vertical and horizontal direction respectively. α is the angle between the two plates. FIG. 8 illustrates the definition of the different parameters (left) and shows the facet of two stacked plates with fibre arrays (right). The average values of the upper mentioned parameters are put in TABLE 2.

x_{av}	σ_x	Δx_{ave}	$\sigma_{\Delta x}$	y_{ave}	σ_y	Δy_{ave}	$\sigma_{\Delta y}$	α
248 (250) µm	6 µm	4 (0) µm	7 µm	249.5 (250) µm	-	1.3 (0) µm	4.8 µm	0.15 (0) degrees

TABLE 2. Experimental results (ideal values are written between brackets). The meaning of the parameters is graphically represented in FIG. 8.

The depth of all the grooves was exactly 126 um ± 0.5 micron to make sure each fibre can be buried in them. The measured vertical positions of the fibre cores are in agreement with this accuracy level, taking tolerances on the cladding diameter into account. However, concerning the lateral precision on fibre position in the horizontal direction, there is still room for improvement. The low average pitch (in comparison to the desired 250 micron spacing) between the cores is most probably caused by a slight error on the demagnification of the mask projection unit and can be adjusted rather easily. The deviation in the X direction can be improved as well by making the grooves smaller. This slightly complicates the introduction of the fibres in the grooves and most probably a compromise will have to be made. Another possible source of horizontal misalignment is the fibre cutting process: the hot knife tends to detoriate the smoothness of the plate facet, and deform and loosen the fibre from the groove in the direction of knife movement (visible in FIG. 8). An alternative method is a second laser cutting procedure for the fibre termination instead of the hot knife technique, followed by a polishing step if required. Both possibilities will be investigated to enhance the accuracy of the core positions.

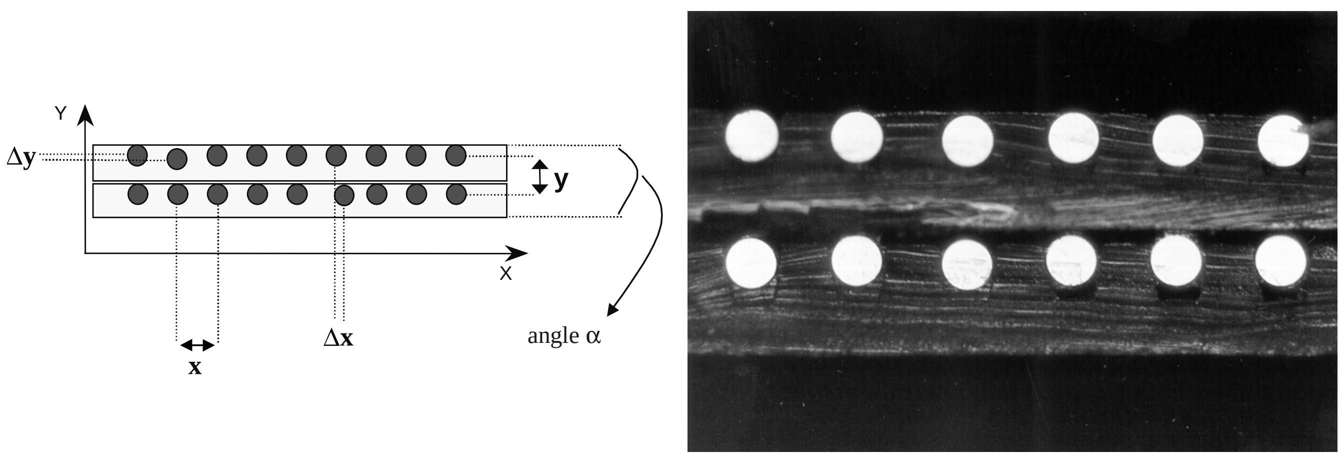


FIG. 8. Definition of the accuracy parameters (left), close-up on 2 stacked plates with fibre arrays (right).

6. CONCLUSION AND FUTURE WORK.

The experiment as explained above demonstrates that the required materials for 2D fibre-connector fabrication with laser ablation are readily available and generate fairly good accuracies. Based on the quality of the grooves, determined by the steepness of the trench profile, accurate control of the depth and the smoothness of the bottom, UV excimer laser ablation proves to be a very valuable technique for fabrication of optical alignment structures in polymer material.

The 2D connector we realised up till now is limited to 2 stacked plates each carrying 8 fibres, but can easily be extended to more stacked groove arrays. The achieved accuracy results are not limited by the ablation process of the grooves itself, and can still be improved by further optimisation of the assembly procedure.

In a next step we aim at the realisation of a 4×8 patchcord including alignment features (e.g. pinholes) which can be accomplished by excimer laser ablation.

7. ACKNOWLEDGEMENTS.

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