PRECISION FOR PHOTONICS

The adoption of photonic chips is currently held back by the considerable cost involved in their production. In particular, optical fibre alignment and fixation have been a bottleneck in terms of product performance, cost and production volume. A new optical fibre array has been developed to couple multiple fibres to a photonic device with sub-micrometer accuracy. To assemble this fibre array in an automated manner, a fibre-array assembly machine has been designed and realised. This machine is able to assemble a 16-fibre array within four minutes with a 100 nm alignment accuracy, which is both significantly faster and more accurate than currently employed methods can achieve.

MATTHIJS VAN GASTEL

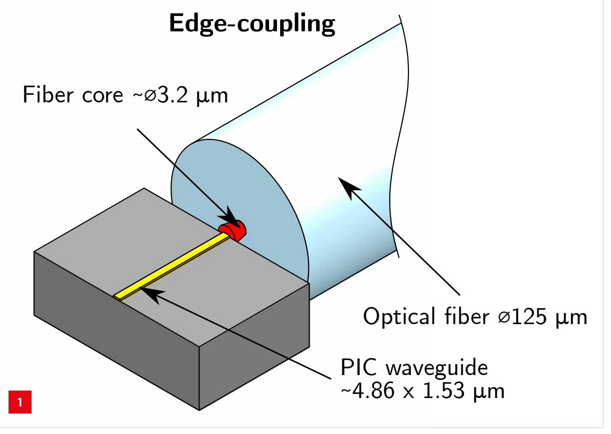
In today's society, the need for data transmission is growing exponentially. Photonic chips show great potential for energy-efficient data transmission with high bandwidth. These chips rely on information transfer based on light as opposed to electrons in the conventional electronic chips.

Photonic chips enable many new applications such as sensors for autonomous driving cars or new medical imaging techniques. An increasingly important issue for enabling large-scale adoption of photonic chips is their assembly and packaging. These processes are currently estimated to account for more than 50 percent of the total cost of a photonic device.

Especially the coupling of optical fibres, which are used to guide light in and out of the photonic device, is critical as they require sub-micrometer alignment. Current fibre alignment methods can either not cope with these alignment requirements or are not suitable for large-scale production. Furthermore, current methods are often labour-intensive and time-consuming.

Current methods

A typical optical fibre is composed of a very thin strand of silica glass with a diameter of 125 μm. The silica glass strand consists of two parts with a different refractive index to enable light guiding: the core and a surrounding cladding. A core as small as Ø 2-10 μm is embedded in the middle of the fibre. This core guides the light, and the surrounding cladding material with a slightly lower refractive index confines the light within this core. To couple light in and out of a photonic chip, the fibre core needs to be aligned with respect to the coupling channels or waveguides present on the chip's side. Figure 1 shows a schematic representation of a fibre-chip coupling. Since a typical photonic waveguide is small (~1-5 μm), a precise fibre alignment is required to ensure efficient operation of the optical components. Especially the alignment in a lateral direction is critical, with a desired alignment accuracy of typically < 200 nm.



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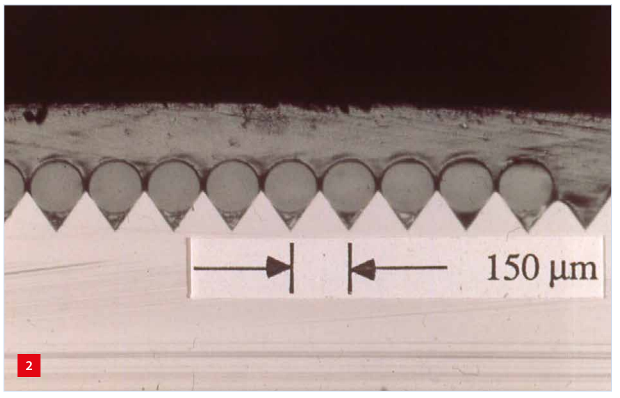
Schematic rendering of a fibre-to-waveguide-edge coupling.

Nowadays, V-groove fibre arrays are typically used for multi-fibre alignment. Figure 2 shows an example of such a V-groove array. For these arrays, multiple optical fibres are placed into V-grooves that determine the position of the fibres with respect to each other. After the assembly of a fibre array, it can be aligned with respect to the waveguides of a photonic device. A major downside of these arrays is the inability to compensate for the manufacturing tolerances of optical fibres and the V-groove array itself, typically resulting in lateral alignment errors of > 2 μm.



2

Passive alignment using a V-groove fibre array.

AUTHOR'S NOTE

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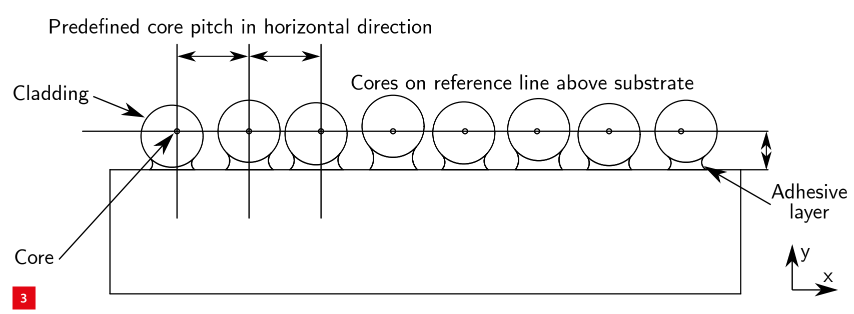


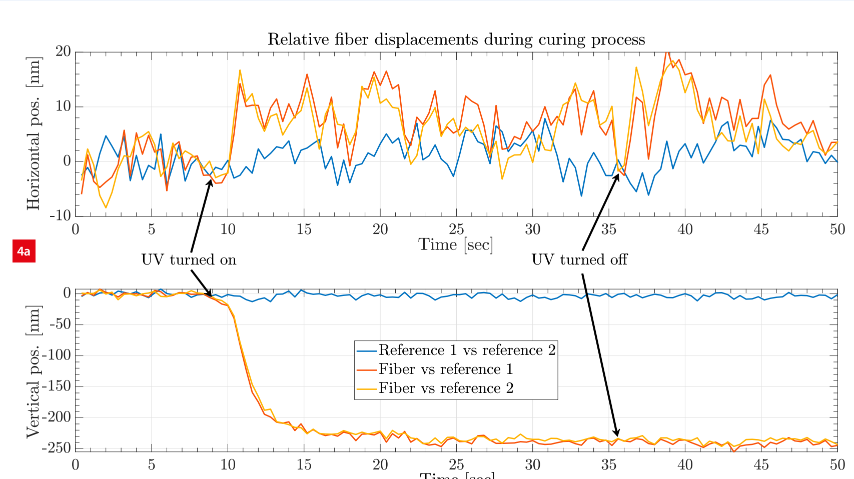
3

The proposed concept of the optical fibre array.

Active alignment methods that use optical feedback to optimise the waveguide alignment are able to compensate manufacturing tolerances of the fibre, enabling sub-micron-accurate alignment. Current active alignment methods, however, are time-consuming, with alignment times of multiple minutes per single fibre connection, and are therefore expensive and not suitable for volume production.

Optical fibre array concept

The main challenge to obtain a low-loss coupling for photonic devices is to overcome the accuracy bottleneck due to the manufacturing tolerances of the individual fibres. In the proposed concept the alignment is split up into two steps. First, a fibre array is assembled with a mutual lateral alignment accuracy of < 0.1 μm between the fibre cores. Later on, this fibre array is assembled in one step to the photonic chip. Since this step is not within the scope of this research, it will not be discussed further. A perfect alignment of the channels/waveguides on the photonic chip is assumed since these chips are made using a lithographic process. In reality, some small chip warpage is present due to the dicing process.
With our decoupled approach we eliminate the risk



Measured fibre displacements during the adhesive curing process. The displacements are shown relative to fixated reference fibres.
(a) Horizontal (lateral) direction.
(b) Vertical direction.

of having to discard an entire chip when a single fibre alignment has failed. Additionally, this allows for dedicated assembly equipment, resulting in faster and more economical production.

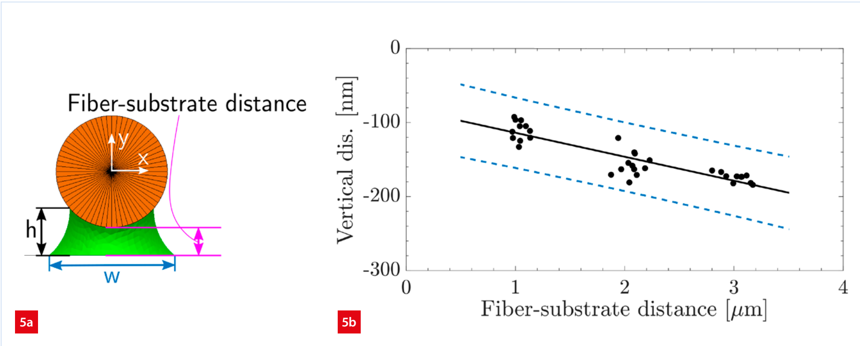
The array, shown in Figure 3, consists of multiple fibres, which are fixated to a flat quartz carrier substrate using UV-curable adhesive. Each fibre is individually actively aligned with respect to the already fixated fibres using a high-precision manipulator before curing. The adhesive layers are used to overcome differences in manufacturing tolerances of the fibres. During the alignment process the cores of the fibres are positioned so that there is no variation in the vertical direction on a horizontal line above the substrate and with a predefined pitch in horizontal direction. By using an adhesive as fixation method, the achievable distance between the fibres can be kept to a minimum since the adhesive only needs to be present on a small portion of the fibre diameter. The usage of a simple flat carrier without the need for any electrical connections or mechanical adjustments results in a cost-effective solution, where the number and pitch of the fibres can easily be varied for specific chip designs.

Adhesive fixation

Adhesives are prone to shrinkage due to curing, which can disturb the fibre alignment. As a result, not the alignment process itself but rather the fixation process forms the bottleneck in reaching the required sub-micron alignment. Simulations and experiments have been performed to investigate the shrinkage-induced fibre displacement for multiple selected types of adhesives. Figure 4 shows the typical fibre displacement due to adhesive shrinkage during the curing process. This figure presents the displacement of the fibre to be cured relative to the two reference fibres that are already fixated. When the UV-curing head is turned on, a clear vertical displacement is observed while simultaneously negligible horizontal drift is observed.

Capillary action results in the formation of a symmetrical bond profile around the fibre when the fibre is brought into contact with the adhesive, which explains the negligible observed horizontal drift.

To measure the shrinkage of selected adhesives, the fibre-to-substrate distance (indicated in Figure 5a) was varied between 1 and 3 μm. This range is sufficient to overcome the most typical fibre tolerances. Larger adhesive layer thicknesses are unfavourable due to a lower bond stiffness and an increased sensitivity for temperature-induced displacements. Figure 5b shows the results of one of the selected adhesives. A negative linear trend can be observed for the shrinkage as a function of the fibre-substrate distance in the examined range of 1 to 3 μm.



Measuring adhesive shrinkage.
(a) Schematic front view of the fibre-adhesive bond geometry (not-to-scale).
(b) The vertical fibre displacement due to adhesive shrinkage as a function of the fibre-substrate distance for one of the investigated adhesives (Nordland Optics 61).

The magnitude of the vertical fibre displacement upon curing lies between 100 and 200 nm, which is in general too large to achieve the required alignment accuracy. The repeatability of the process is however quite good, with a maximum 3σ-prediction bound of approximately –35 nm to +35 nm for the linear least-squares fit through the shrinkage measurement points, which is more than sufficient for the most critical fibre alignment applications. This linear fit is used to apply an offset to the position of the fibre before curing, in order to reach the desired alignment.

Environmental tests have been performed to evaluate the long-term stability of the adhesives since these are prone to mechanical creep and stress relaxation over time. The results of these tests indicate a sufficiently dimensionally stable adhesive bond for photonic fibre alignment with a 3σ position reproducibility of 110 nm.

Fibre-array assembly machine

To assemble the proposed sub-micron-accurate optical fibre array in an automated manner, a fibre-array assembly machine has been designed and realised; see the overview in Figure 6a. By automating the assembly process, a repeatable process is possible for volume production while the assembly costs are simultaneously reduced. The design of the alignment machine comprises three motion axes: a horizontal x-stage, a vertical y-stage and an axial z-stage. Both the vertical and the axial stage are connected in series to the horizontal stage.

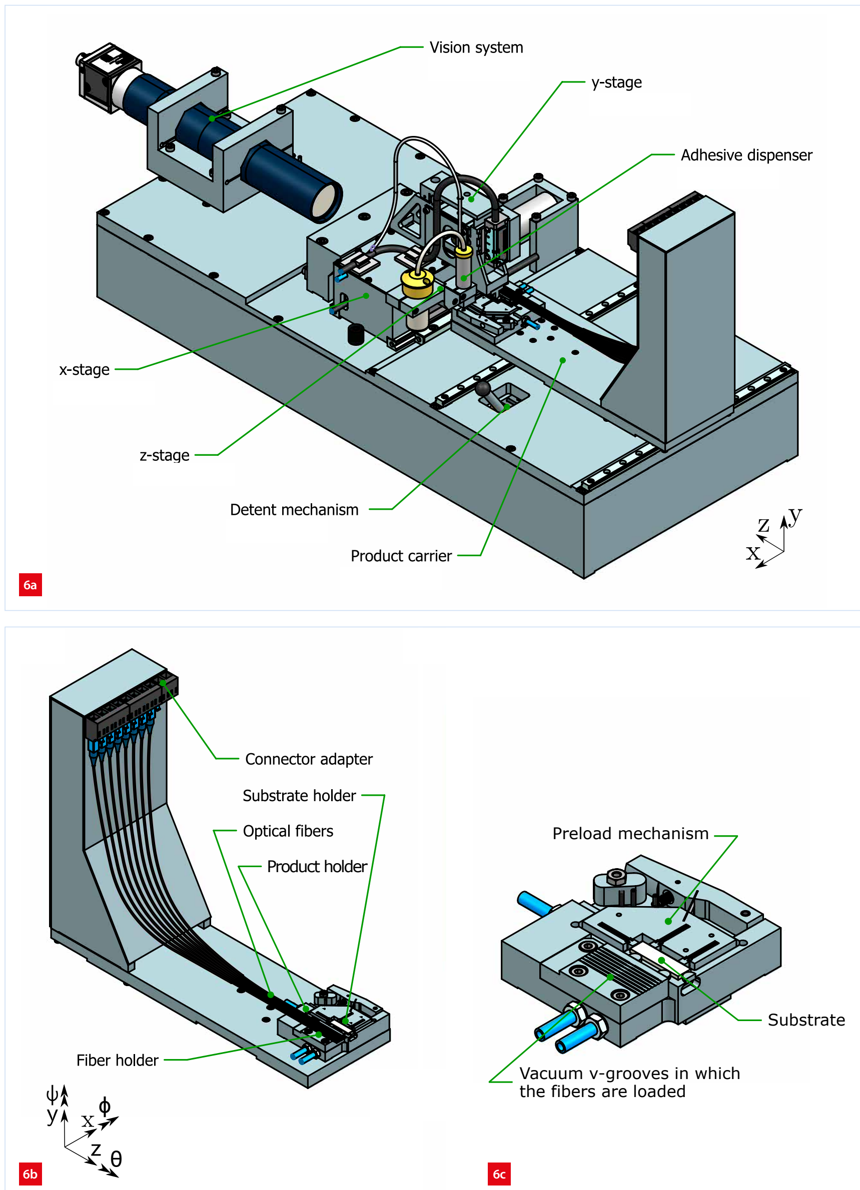
The following main production steps are executed by the machine to assemble an optical fibre array.

Pre-alignment

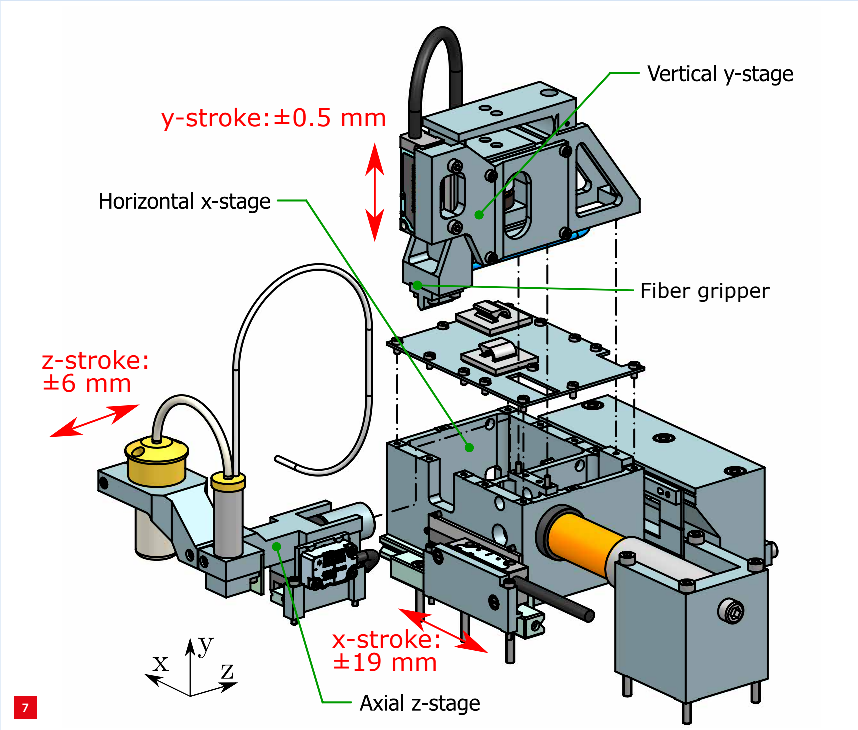
As input of the machine, a product carrier (Figure 6b) is used to which pigtailed optical fibres and a quartz substrate are manually loaded into a product holder (Figure 6c). The fibres are held in vacuum V-grooves in a fibre holder while the substrate is preloaded against end-stops and clamped using a vacuum. The product holder is used to determine the position of the fibres and substrate with respect to the other components of the machine. The holder is mounted onto linear guides, which enables loading and unloading of the fibres, substrate and arrays away from the alignment station. A detent mechanism is used to horizontally align the product holder relative to the other components of the alignment machine during a production run.

Axial z-alignment

A flat end-face mounted to the axial z-stage is used to mutually align the fibres passively in the axial degree of freedom (DoF). Using the z-stage, the end-face is pushed against the front surfaces of the fibres until all fibres in the vacuum V-grooves of the fibre holder will slip and align axially with each other.



The designed and realised fibre-array assembly machine.
(a) Overview.
(b) The product carrier.
(c) The product holder.



Overview of the motion axes of the fibre-array alignment machine. Indicated in red are the strokes of each axis.

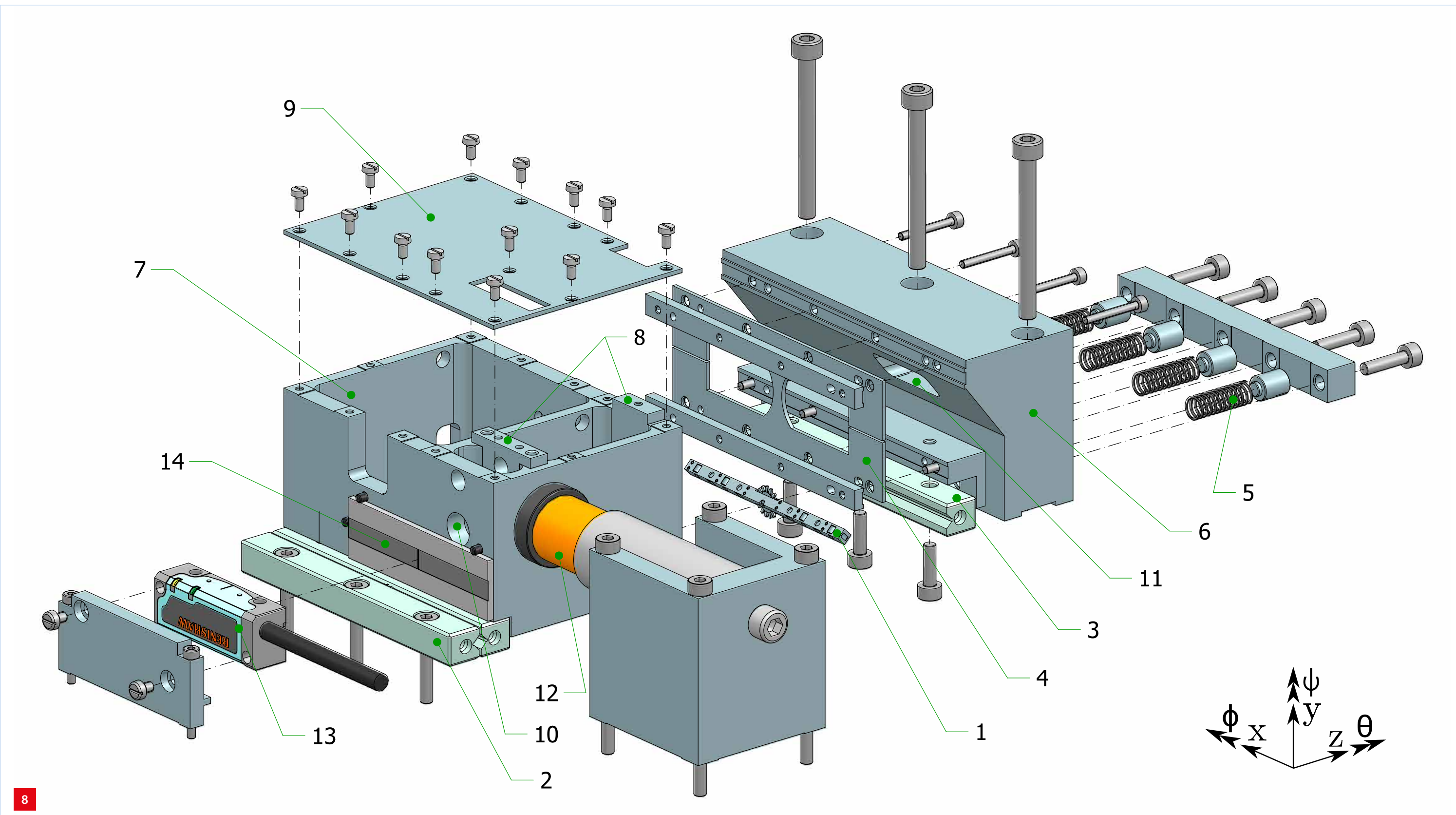
Adhesive dispensing

The fibres are fixated to the substrate using adhesive. An adhesive dispenser, mounted to the axial *z*-stage, is used to dispense multiple droplets in a straight line on the substrate.

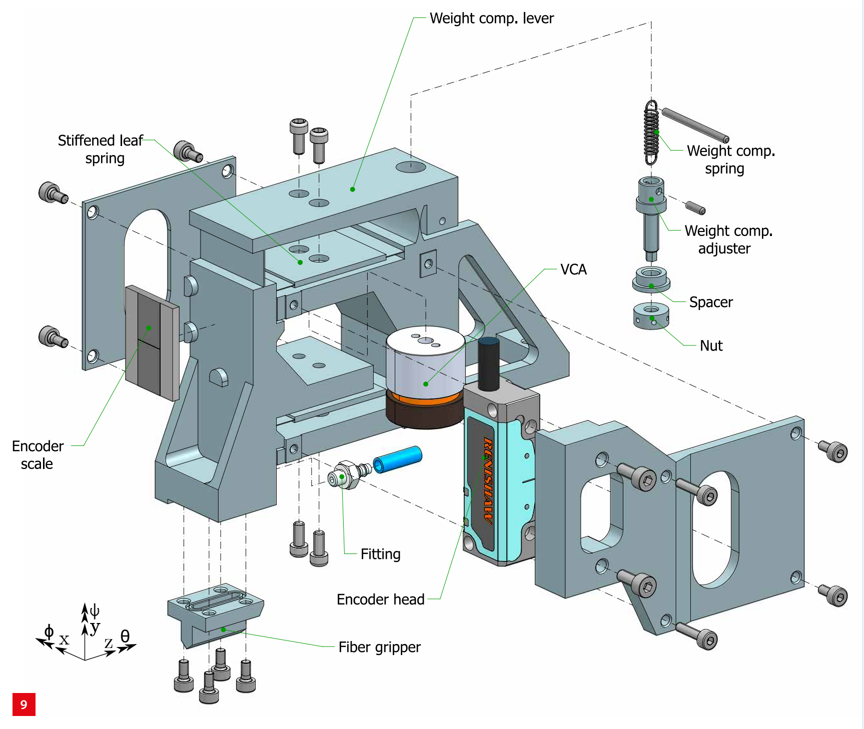
Active alignment

The vertical *y*-stage is used to pick up fibres out of the fibre holder using a vacuum V-groove fibre gripper (the high-precision manipulator referred to above and explained in more detail below). Together with the horizontal *x*-stage, the *y*-stage actively aligns each fibre in the *x*- and *y*-DoFs with respect to already fixated fibres and reference fibres present at the product holder. The lateral *x*- and *y*-alignment directions are the most critical ones for obtaining an efficient fibre-chip coupling.

For the active alignment process, light is guided into the fibre connectors. A vision system is used to determine the fibre core positions. Contrary to traditionally used optical power measurements for active fibre alignment, both the current fibre position and the desired target position are instantly known when using the vision system, thus reducing the alignment time. A calibration method has



Partial exploded view of the horizontal x-stage.
1. Crossed-roller cage.
2. Main guide rail.
3. Secondary guide rail.
4. Hinged leafspring.
5. Compression spring.
6. Leafspring support.
7. Carriage.
8. Support point y-stage.
9. Top plate.
10. Carriage vision hole.
11. Support vision hole.
12. Voice-coil actuator.
13. Incremental optical encoder.
14. Encoder scale.



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Exploded view of the vertical y-stage.

been developed for the vision system based on error-separation techniques to achieve both a relative and an absolute measurement accuracy of < 100 nm required for the generation of motion setpoints for the fibre alignment. The V-groove of the *y*-stage's fibre gripper is used to passively determine the less critical and not actively aligned ϕ- and ψ-DoFs.

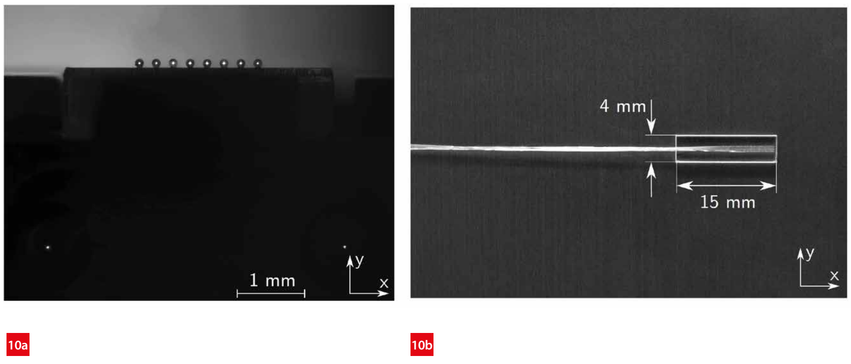
Motion axes

Figure 7 gives an overview of the motion axes including the motion directions. To minimise hysteresis and friction and allow for a high positioning resolution and control bandwidth, all three motion axes are actuated using voice-coil actuators. For position feedback of the axes, optical linear encoders are used, which are placed as close as possible to the output while maximally satisfying the Abbe criterion to minimise measurement errors.

The horizontal *x*-stage (Figure 8) of the machine consists of a closed box to attain a lightweight and stiff construction and is guided over a stroke of –19 mm to +19 mm using a linear, force-closed, statically determined crossed-roller bearing. The selection of this guidance results in a cost-effective, compact and stiff solution that can be easily maintained while a low friction and backlash is simultaneously attained. The main guide rail of the stage is directly fixated to the frame of the machine. The secondary guide rail is supported on a hinged leafspring and preloaded using multiple compression springs to obtain a force-closed, statically determined guidance. Experiments show that this guidance has a friction of less than 0.015 N, resulting in steady-state positioning errors of 5 nm (limited by encoder quantisation).

The vertical *y*-stage of the assembly machine (Figure 9) is provided by a flexure-based parallelogram straight-guide mounted to the closed box frame of the horizontal stage. The flexure-based parallelogram results in a backlash-free and frictionless motion over a stroke of –0.5 mm to +0.5 mm with a residual stiffness of 1,100 N/m and a first, bandwidth-limiting eigenfrequency of 865 Hz. A vacuum V-groove fibre gripper is integrated in the bridge of the parallelogram to pick up and place fibres, and simultaneously provide a passive fibre alignment in the other, not actively aligned, fibre DoFs, as enabled by the V-groove geometry. Due to this gripper geometry, only a fraction of the fibre circumference is retained by the gripper, allowing for a minimal fibre pitch of 127 μm (fibre diameter is 125 μm). To reduce power dissipation by the *y*-stage and prevent damage to the fibre gripper during a shutdown, a weight compensation mechanism is integrated in the parallelogram flexure.

The axial z-stage, fixated to the bottom of the closed-box frame of the horizontal stage, uses a linear guidance with running crossed-roller cages to move a dispenser head and glass end-face over a stroke of –6 mm to +6 mm. By translating the glass end-face mounted to this stage, the fibres are pushed back in the fibre holder to obtain a mutual axial *z*-alignment with an, experimentally determined, 50 nm repeatability. A non-contact dispensing system based on inkjet depositing is used to dispense multiple small adhesive droplets (Ø ~150 μm each) over a 10 mm line to enable dispensing near the already fixated fibres for fibre pitches down to 127 μm. After alignment, the adhesive is cured from underneath the substrate using a LED UV head focused by an optical system to obtain a homogenous and fast cure that will not disturb the fibre alignment.



10a 10b

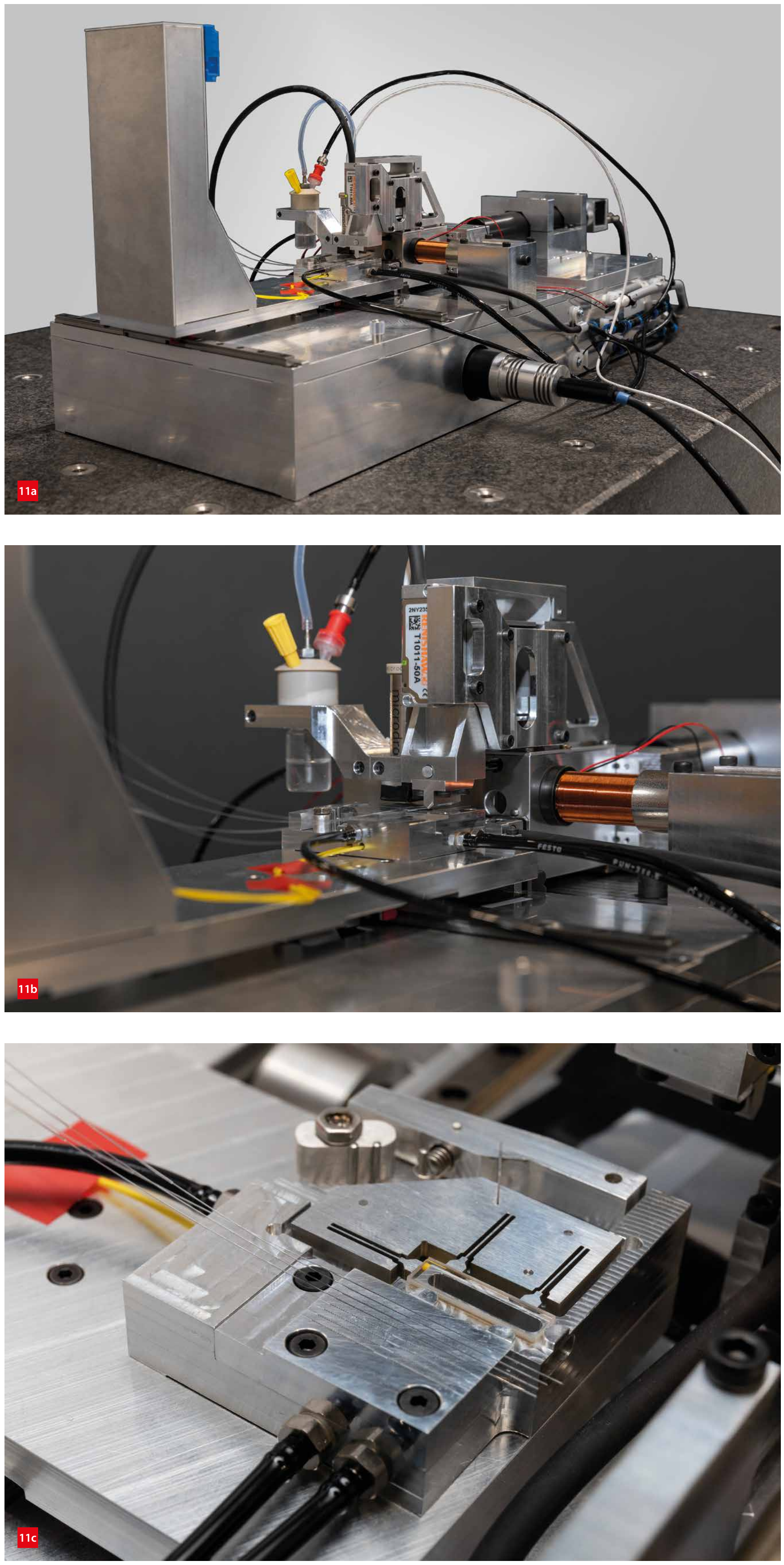
An assembled 8-fibre array with a 250-μm fibre pitch.
(a) Front view.
(b) Top view.

The thermal input to the assembly machine is simultaneously minimised due to the required short curing times and low power dissipation by the LED UV source. The thermal sensitivity of the metrology loop is significantly reduced by employing the two reference fibres located close to the substrate, since thermal drift between the substrate holder and vision system can be detected and compensated for both the lateral (x,y) directions and when rotation occurs around the camera axis. The thermal sensitivity of the metrology loop is reduced further by making the main components of the assembly machine from aluminium (high thermal diffusivity) and using a telecentric lens for the vision system (parallax error elimination).

Results

To assess the performance of the realised fibre-array assembly machine, multiple fibre arrays were assembled, each with a different number of fibres and a different fibre pitch, as small as 127 µm. Figure 10 shows both a front and a top view of an assembled array. The machine is able to assemble a 16-fibre array within four minutes. This is significantly shorter than currently employed active alignment methods can achieve, typically taking multiple minutes per single fibre connection. The curing of the adhesive takes approximately 68 per cent of the required production time and is therefore the major bottleneck for achieving shorter production times. By employing a faster curing adhesive, a significant reduction in the total production time of an array could be achieved.

During the assembly of ten 4-fibre, 250-µm-pitch arrays a maximum fibre alignment error of 81.9 nm was observed in the x-direction while a maximum error of 71.7 nm was observed in the y-direction. This is more than accurate enough for the most critical fibre alignment applications. When compared to traditionally employed V-groove arrays, an approximately eight times smaller alignment error in the x-direction and an approximately eighteen times smaller error in the y-direction was observed for the machine-assembled arrays, demonstrating a clear performance advantage. Figure 11 shows the realised fibre-array assembly machine.



The realised fibre-array assembly machine.
(a) Overview.
(b) The motion stages.
(c) The product holder.