Requirements for process automation of optical interconnect technologies

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14.1 An introduction and a list of issues

This chapter will concentrate on the need for automation of the packaging of PICs, and will not address the system-level integration of silicon photonics at board level/backplane/enclosures/inter-rack connectivity [1], partly because PIC packaging is where the authors are more knowledgeable, but also because it is felt that automation of the PIC packaging processes—and the inherent cost savings—is and will be an important first step, and will be largely responsible for widespread acceptance of PICs.

From wafer level to a fully packaged photonics device the path is fairly long and requires the assembly, alignment, testing, and integration of several elements/process steps, but essentially packaging should take care of the following:

- Complete the photonics circuit with the additional elements not integrated at wafer-level, typically with a flip-chip bonding process;
- Insert the chip into a "box" (the package) that provides mechanical and environmental protection to the device (bath-tub metallic packages, ceramic or organic/plastic packages;
- Provide electrical connectivity (wire-bonding inside the package, pins outside the package);
- Provide optical connectivity (single/multiple fiber optics pig-tailing);
- Ensure thermal contact/thermal interfacing for proper power dissipation.

The path is equally long also from the manual assembly of complex PIC devices in the labs that relies on very skilled and patient personnel, with a single device assembly time that can span over several hours with uncertain yields, to a full industrial production targeting minutes or possibly tens of seconds per device, with extremely high yields and very repetitive and accurate processes.

14.1.1 Let us pick an example

The example in Fig. 14.1 is taken from Doe [2], and shows a single photonic chip produced at wafer level with well proven CMOS foundry technology. An external CW infrared laser source is mounted on the diced chip, with the beam facing down and coupled via a grating structure to the optical circuitry of the chip. A bundle of

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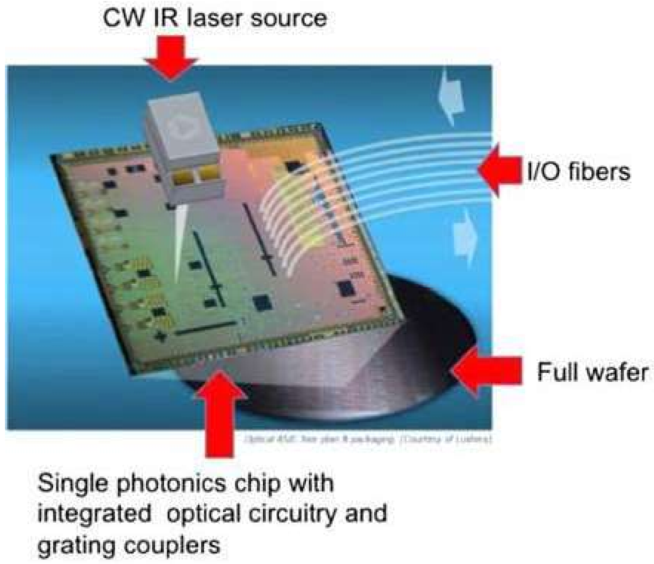

Figure 14.1 An example of a photonics chip assembly.
Source: Courtesy of Luxtera.

fibers carrying the input and output signals is also shown. The fibers will typically be assembled in a ribbon and pre-spaced on a glass block. The laser source and the fiber block have dimensions of a few millimeters, and require positioning with submicron accuracy. Epoxy glue bonding is used to fix these components to the silicon substrate. These kinds of operations represent the core of automated PIC packaging/assembly.

It should be noted that the example above does not show an actual outer package and more conventional process steps, for instance wire-bonding.

14.1.2 Complexity levels in packaging processes and the evolution of assembly machines

The level of complexity of PICs can cover a very broad range, from fairly simple TOSA/ROSA to a multi element free-space optics hybrid assembly of a full transceiver, as illustrated in the following figures. In a similar way, dedicated assembly machines have evolved from R&D laboratory equipment or compact demonstrators to fully-fledged automated industrial equipment.

The assembly in Fig. 14.2 shows a single fibers aligned to a photo-detector and held in position by a fairly large "glob" of laser-induced soldering. This fixing method requires a metallized fiber, and it is no longer in use today. This assembly can hardly qualify as a PIC as it is really an assembly of parts, including SMT passive components, on what looks like a ceramic substrate.

A more recent PIC assembly is shown in Fig. 14.3: a chip is held in a chuck and is being contacted by an electrical probe-card on the left, while a fiber-array block is being positioned from the right.

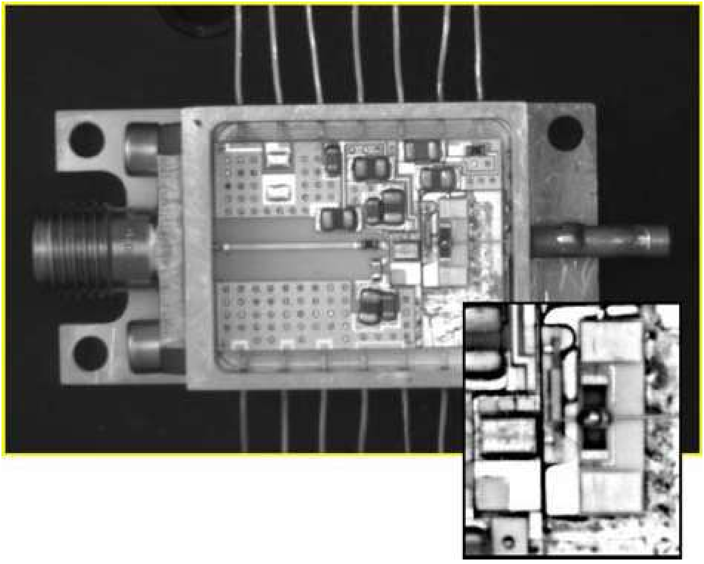

Figure 14.2 An optical receiver from the mid-1990s.

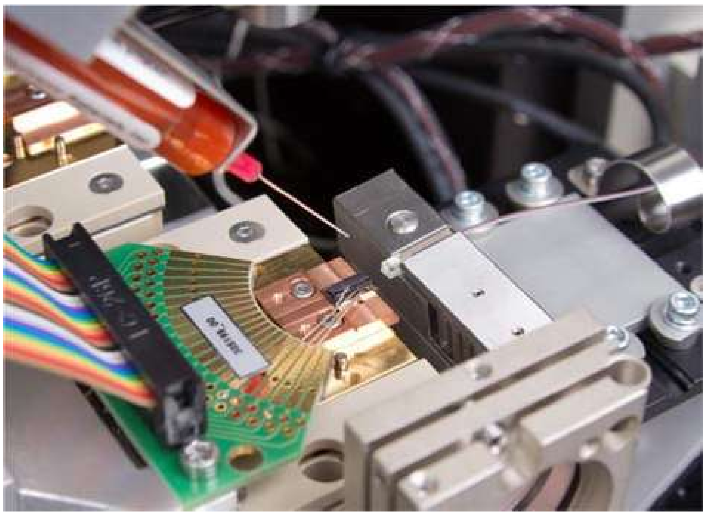

Figure 14.3 A photonics chip being coupled to a fiber-array block.

A device with a much larger complexity, a transceiver that also requires the bonding of free space micro-optical elements, is illustrated in Fig. 14.4. The actual device is held on the chuck between the two electrical probe cards and micro-optical elements are aligned on its right-hand side.

To address the evolution of machines, a few examples are illustrated below, starting with a picture from 2001. While it is true that the motion mechanics has also progressed since then, the wide availability and cost reduction of "accessory" technologies like machine vision, nanometer-resolution of position sensors, industrial computer processing power, and tools for faster software development, is largely responsible for the transition to fully automated industrial machines.

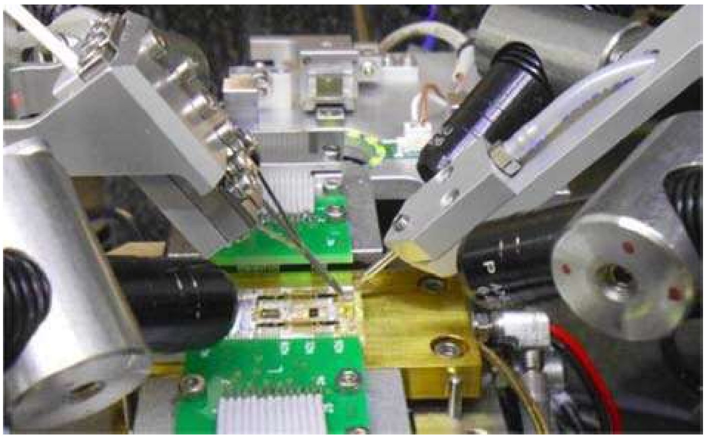

Figure 14.4 A complex transceiver assembly with free-space micro-optics elements.

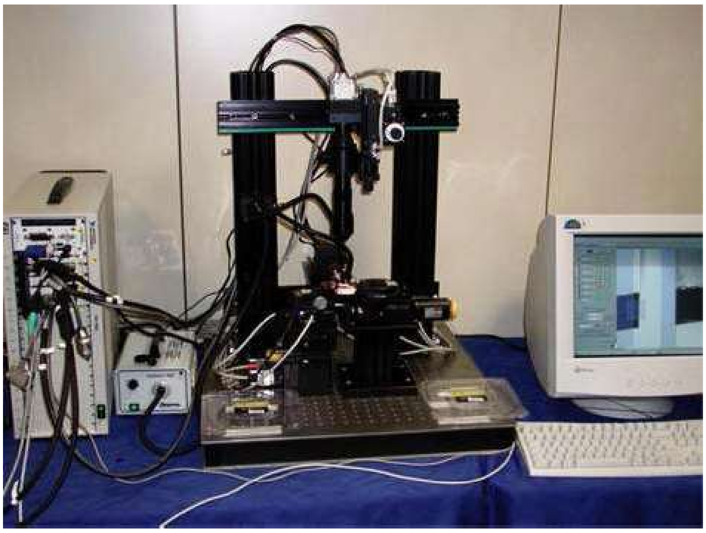

Figure 14.5 An active alignment demonstration unit developed by miCos GmbH and National Instruments Italy in 2001.

What we see in Fig. 14.5 above is a table-top five-axis mechanical set up targeted at demonstrating fast active alignment. It is complete with high-magnification cameras and is fully controlled by the PXI-based industrial controller on the left, housing also the motion control, image frame-grabbers, and data acquisition boards.

A more complex set up with a total of 14 mechanical axes is shown in Fig. 14.6, with the 3D mechanical layout and a detail of the fiber-arrays block held on electrically heated grippers (for thermal epoxy bonding). The primary goal was active dual-sided fiber optic pig-tailing of a new type of modulator with edge-coupling optical input output. With a typical coupling area of $1.5 \times 5\ \mu m$, the required accuracy to minimize losses was in the order of 100 nm, with a minimum controlled

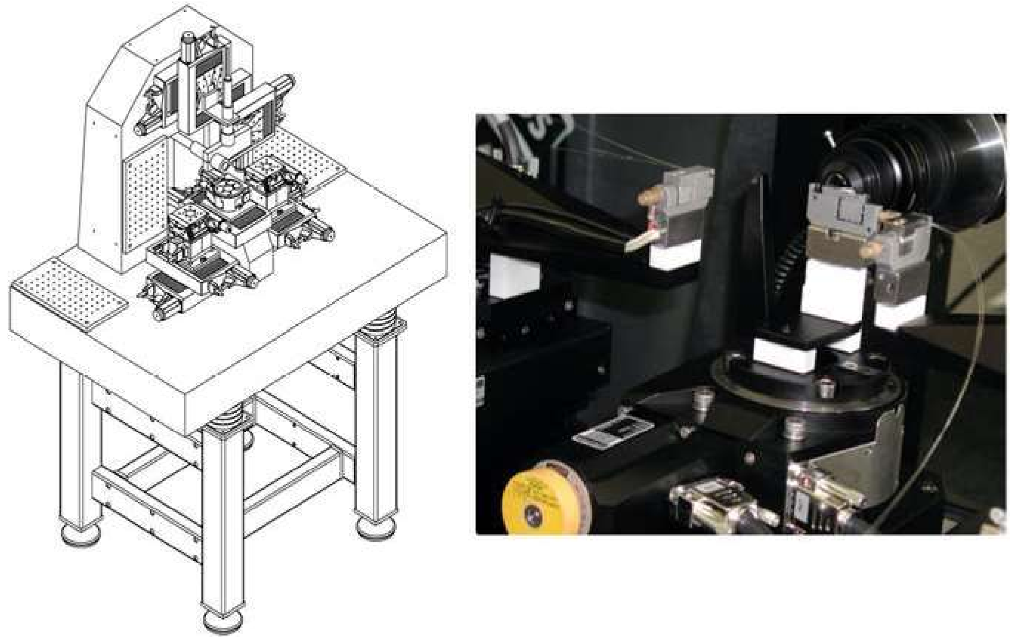

Figure 14.6 A 14-axis dual-sided FO pig-tailing machine at Pirelli Labs in 2001.

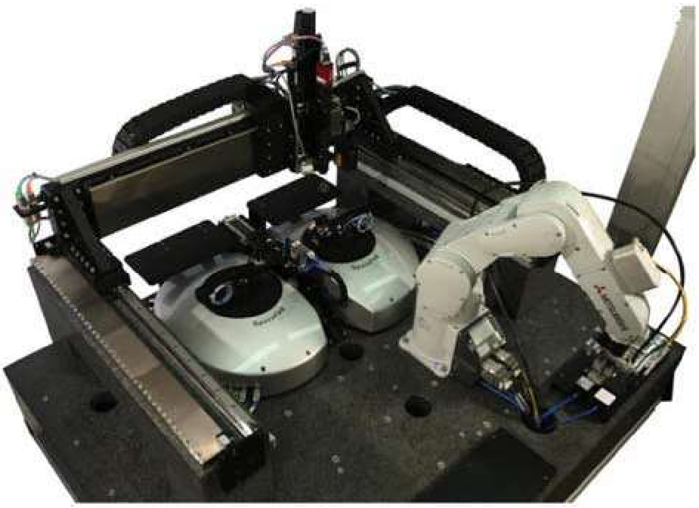

Figure 14.7 A pre-production PICs assembly machine designed and built in 2013.
Source: Courtesy of PI-miCos.

step of the alignment mechanics of 25 nm. Synchronizing power meter data acquisition and motion control was challenging at that time, and it is further explained in Section 14.2.

In Fig. 14.7 we jump ahead some 12 years. The machine depicted was designed with a strong accent on flexibility, as it was targeting the pre-production of a limited batch of PICs and would then serve as a generic assembly platform at CNIT-Inphotec in Pisa, Italy [3].

Figure 14.8 A series of industrial PICs machines being commissioned at ficonTEC GmbH in 2015.

Within this long period of time two things are worth remarking on: vertical optical coupling based on grating structures had become widely used in PICs, and an alternative to the stack of axes in the assembly machines had emerged in the form of parallel kinematic hexapod-like 6 DOF mechanical devices. On this machine, ancillary operations like the pick and place of the components to be assembled, as well as epoxy-glue dispensing and UV curing, are performed by an of-the-shelf 6-axis anthropomorphic robot.

As the demand for volumes increased more functionalities were added into the machines, with fully automated long sequences of operations, including multiple-components pick and place, epoxy dispensing or laser welding/soldering, in-line testing, etc. The look of the machines also changed, with full outer enclosures, larger buffers/loaders for parts, and a top-mounted tri-color semaphore signaling machine status. A series of such machines being commissioned prior to delivery can be seen in Fig. 14.8.

The key "ingredients" of these machines are further presented and discussed within thischapter.

14.1.3 The main steps of a complex packaging process

In the world of conventional semiconductor devices, the terms front-end/back-end usually refer to wafer-level processing and the following processes to package the semiconductor die. Some of the semiconductor fabrication steps are also common to photonics, and are simply adopted for the packaging of PICs, but not all the steps need to be included in a PICs assembly machine. Electrical wire-bonding is a good example: this process has reached such a level of optimization that it would not make sense to include it in machines dedicated to PICs. Furthermore,

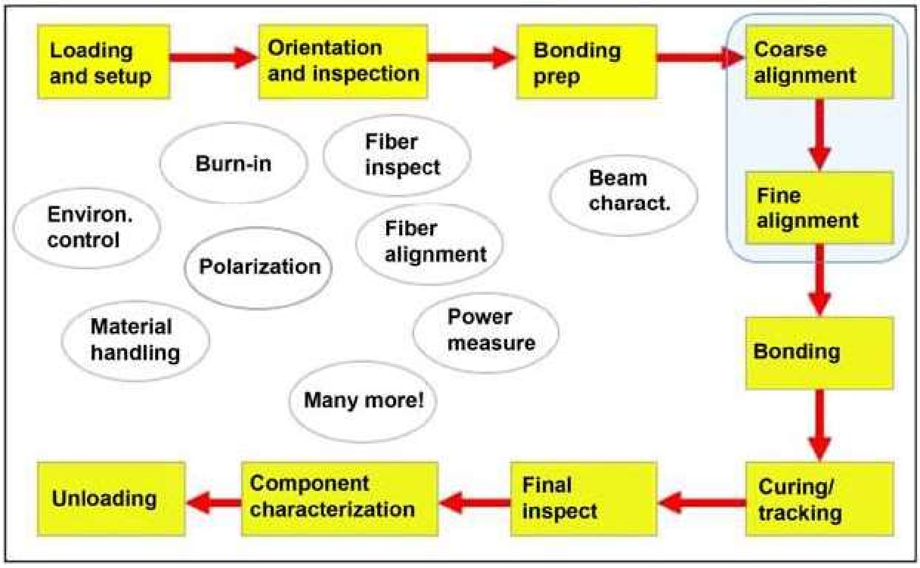

Figure 14.9 The steps of a typical assembly process from a 2002 presentation.

specific equipment is offered from reputable suppliers with very good price/performance ratios, only achievable when technologies have stabilized for decades. The sub-components of PICs are in most cases delivered as pre-diced wafers on what is commonly termed as blue-tape, in gel-packs, waffle-packs, or ad-hoc loading trays.

The actual sequence of process steps is invariably specific to a given PIC device, requiring some form of sequencing flexibility/programmability to be designed into the assembly machine. Fig. 14.9 recycles an old slide of a speech given in 2002 by one of the authors during a workshop at Flextronics, in Cork, Ireland, but it is still very much applicable today. The square boxes list the actual process steps from the loading of parts to the unloading of the completed assembly, while the bubbles add additional/auxiliary topics of the assembly process. Coarse and fine alignment are in today's jargon often replaced with passive/active alignment, as discussed in Section 14.2.

Some form of flip-chip bonding is often part of the process in order to add additional components to the optical circuitry chip, ranging from complex CMOS driver circuits for multiple MZ modulators, making use of micro-copper pillars [4] or other "bumps" contacting methods, to single devices like laser emitters or photodetectors. The latter devices are often in the form of CoS (Chip on Sub-mount), and are attached with a variety of bonding methods, from epoxy gluing to laser-induced soldering.

Listing all the required/possible steps is outside the scope of this short chapter, and the assembly of photonics devices is still in a growing phase, with new ideas, methods, and "tricks" being disclosed at every conference. A consequence of this is that in the design of a complex automated machine, the first step is always the careful analysis of the device assembly process.

14.1.4 PIC numbers, machine builders, and the flexibility versus speed issue

Production volumes obviously have a great impact on a machine's development and evolution, but when it comes to PICs numbers, accurate figures are hard to get. Some data are provided by colleagues of IMEC [5] in reference to CMOS 12″-equivalent wafers, with 1000 chips per wafer:

- 25 million wafers were produced in 2014 for conventional CMOS chips;
- 25 thousand CMOS PIC wafers per year are required, based on the needs of the datacom market;
- 250 thousand PIC wafers per year could be reached by 2025.

More detailed information is contained in the cited references, but it is likely that the large semicon machine manufacturers have hardly seen a "photonics beep" on their radar screen, and that PICs assembly is still the domain of few, highly specialized, and fairly small, automated equipment manufacturing companies. The variety of packaging solutions, coupled with a lack of packaging standards, demands that today's machines should prioritize flexibility rather than speed, allowing the end users to quickly adapt their equipment to process changing, moving on from early prototypes/limited series, to production-optimized devices.

As PIC production volumes will increase, the design of the machines will likely change, targeting speed rather than flexibility, resulting in "arrays" or lines of simpler machines, interconnected by suitable transport mechanisms for the devices being assembled, and allowing to distribute/parallelise/balance the time duration of specific steps in the whole process. Addressing speed will also address the issue of capital equipment cost and ROI, with a better definition of assembly cost per device. Foot-print, and space requirement in the clean-room, will also become more important, as well as running costs of the assembly machines.

14.1.5 Photonics materials and optical fibers pig-tailing

While the quest for the ideal photonics materials goes on, and while it is clear that in terms of volumes existing CMOS foundries are and will play a major role in the development of photonics, the average machine manufacturer remains reasonably agnostic in the debate over indium phosphide, silicon on insulator, lithium niobate, etc.

A certain degree of "mix and match" of photonics elements based on different materials is likely to be around for quite a while, and getting fibers pig-tailed to the package will also remain, even if a suitable method for passive-only alignment should be developed.

14.1.6 Addressing different markets

This book is about optical interconnects for data centers, but photonics covers many other fields and so does the assembly of PICs. The development of automated assembly processes will benefit from the variety of different application fields and different packaging requirements. A non-exhaustive list is given below:

- High performance computers interconnect with photonics technologies that share most of the needs of data center interconnects;
- Life sciences, with lab-on-chip devices adopting photonics technologies;
- Image sensing, 2D and 3D, for the smart phones and consumer markets, where the assembly of the CCM (Compact Camera Modules) is reaching overall sizes and complexities requiring PIC-like assembly processing;
- Sensing in general, especially based on laser interferometry and multi-spectral analysis, where whole set ups, occupying in the past whole optical breadboards, in the labs are being squeezed down at chip sizes;
- Sensing for automotive, addressing the needs of autonomous vehicles, and combining visible and IR image sensing, LIDAR, motion and gesture recognition sensors. V2V (vehicle to vehicle) and V2I (vehicle to infrastructure) and dynamic map/info updating will also contribute to increase the demand for overall data flows, and hence more data centers;
- Photonics and micro-fluidics, addressing different needs from bubble-based cross-matrix switching for datacom, to bio-medical and life sciences applications.

14.1.7 The more that can be done at wafer level, the better

Most of today's PIC-based devices are assembled/packaged at single die level, usually on pre-tested chips. Another effect of the increase in production volumes will be an effort to perform assembly operations at wafer level, i.e., before dicing.

Conventional semiconductor manufacturing is also moving more and more to 3D assemblies—with some issues on thermal dissipation and increasing numbers of electrical interconnects—and some technologies will spill out to photonics.

Complete wafer-to-wafer bonding is unlikely to occur for photonics devices, at least for the time being, and as long as individual elements need to be added to the PIC substrate, but the mounting of photonics components, including micro-optics elements, onto a complete PIC wafer, prior to dicing, is already being done. Wafer level testing/in-line testing (see Section 14.8) will become more relevant in this context.

14.2 Positional accuracy and the debate on passive/active alignment

There is a substantial difference between accuracy, repeatability, and resolution of the multi-axis mechanics that are used to position and align the components of photonics devices. While the combination of conventional motor-driven mechanics and piezo-actuated elements can easily provide resolutions of a few tens of nanometers, achieving bidirectional repeatability to sub-micron level in industrial-grade, robust, and reasonably priced equipment is still challenging. However, it can be safely stated that mechanical sub-micron repeatability of 0.5 or even 0.05 μm is now achievable by higher class multi-DOF positioners. The repeatability just stated also corresponds to the large majority of user-defined requirements, in order to minimize coupling losses, especially when fibers are aligned to either vertical grating or edge-coupled structures.

Before discussing further let us define what is passive and what is active:

- Passive alignment refers to using machine vision to identify the geometric boundary of a given component (single fiber, fiber array, laser emitter, photo-detector, micro-optical element), and place it on the photonics chip surface. It is assumed that a geometric calibration has been performed between the pixels of image space and the actual encoders of the mechanical axis.
- Active alignment refers to actually "switching on" the component(s), ensuring that a continuous light path exists between a light source (typically a laser) and a detector. The detector can be an optical power meter with a calibrated power output, or a simpler photo-detector connected via a TIA to a data acquisition analog input board. The controllers of the mechanical axis and the data acquisition electronics must share a common clock—or some other form of synchronization—in order to acquire data points that are linked to specific positions in space, and hence determine the best coupling alignment.

Machine vision will reach its limits, mainly due to diffraction or MTF limits of the sensor-optics combination, but it is often used to limit the peak search area of the active alignment. This two-step approach has been also referred to as coarse + fine alignment (see Fig. 14.9 in Section 14.1.3).

Passive versus active is often hotly debated during workshops, as it is considered fairly complex to implement and especially time-consuming. While it is likely that development of pig-tailing methods that are more position/alignment tolerant—one example is the use of micro-lenses to defocus/refocus the light path from PIC to fibers—will continue and mature, it is unlikely that active alignment will disappear any time soon from the requirements of the PICs assembly machines. With today's technology, active alignment can be reduced to a few seconds, and it is worth remembering that it is only one step in a more complex assembly process.

Active alignment has been around in some form or another for a long time—Fig. 14.10 is from 2002—and it is today extremely robust and reliable. The user interface panel in the figure shows the alignment of a fiber-array to a fiber-array performed acquiring the power signal on the first and last fibers of the array (blue and red in the 3D graph). The search area is quite wide by today's standards, and 4000 data points were acquired along an Archimedes spiral motion trajectory (the mechanical interpolation inaccuracies are clearly visible) in some 60 seconds. An important issue of that period was to overcome any latency in the communication between the motion control board and the analog acquisition board, a problem completely settled today by fast CPUs and fast computer busses [6]. At the end of the search, the fibers will be positioned over the maximum peak and monitored during the epoxy bonding curing time, effectively providing also a "bond tracking function".

Fast alignment can be achieved on both a conventional and a piezo-driven axis, and it is today possible to contain active alignment time down to a few seconds. However, adopting a combination of conventional and piezo motion integrated on the same mechanics and completed with a dual loop controller, would allow fast

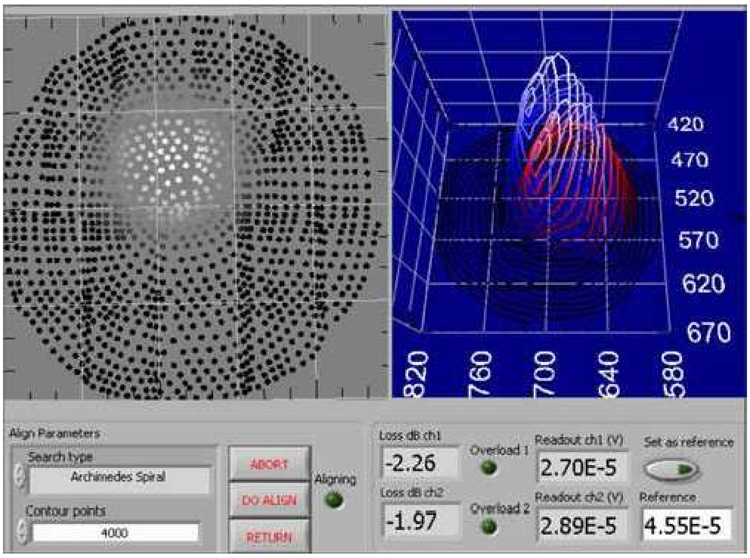

Figure 14.10 An early example of dual-fibers active alignment (2002).

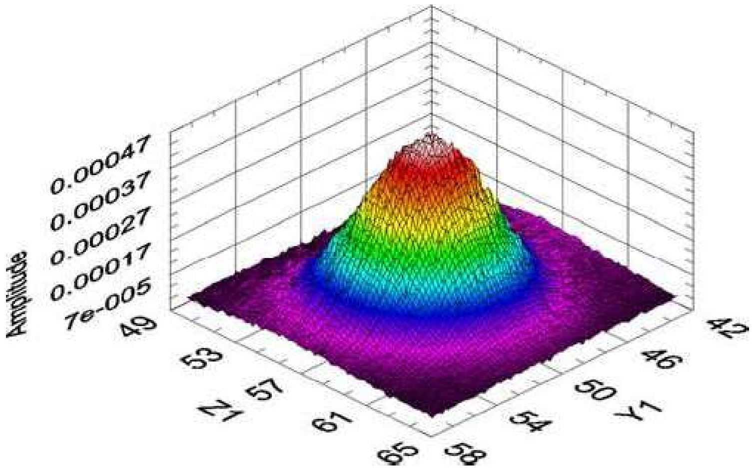

Figure 14.11 Fast alignment check on an area of approximately 18×18 μm.

and large travel ranges to be combined with the resolution and repeatability of short travel piezo actuated flexure stages.

The active search area can also be greatly reduced by guiding the fibers (or whatever component needs to be aligned, like a micro-optical lens) with machine vision to a position that ensures that ensures a continuous path from the light source and the detector, usually referred to as “first light”.

High-speed alignment algorithms coupled with dual sided alignment set ups are particularly relevant for PICs testing (see also Section 14.8).

The 3D plot in Fig. 14.11 depicts a quasi-Gaussian fast peak search over an area of approximately 18×18 μm. Some measurement noise is evident on the plot floor.

14.3 Machine "ingredients" and machine technologies

What makes PICs automated assembly machines complex and thus rather costly is the variety of different devices and technologies that need to be integrated. Ideas and solutions can be mutuated from other industrial automation fields, but they need to be scaled-down to the size and positioning accuracies of the photonics components. The following paragraphs are a non-exhaustive list of the main ingredients. Successful assembly equipment suppliers have managed to turn the mix of ingredients listed below into a set of interlocking modules, preserving both a high level of design flexibility, as well as reducing NRE (non recursive engineering) costs.

14.3.1 Mechanical positioners/manipulators

The core of the machines is heavily based on the combination of motion axis or stages, arranged in different configurations, from overhead gantries, to *x*-*y* tables, rotation wafer chucks, and multi degree-of-freedoms (DOF) assemblies. No attempt is made here to delve into details such as bearings, guides, shaft-couplings, and the myriad of stages sub-components.

14.3.1.1 Stack of axis

The earliest and simplest implementation of multi-DOF is obtained by "bolting together" a number of individual motor-driven axes. Thus, for a full 6 DOF stack (X, Y, Z, θX, θY, θZ) three linear axes and three goniometers are required, as can be seen in Fig. 14.12. Great care has to be taken in the assembly to ensure

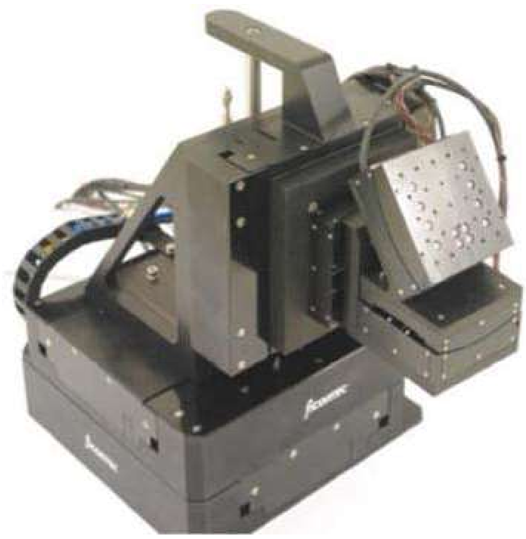

Figure 14.12 A 6-DOF stack of axis.
Source: Courtesy of ficonTEC.

orthogonality and centering of the axes, with some metrology performed on the assembly using interferometry measurements.

A concept that greatly simplifies the operation of multi-DOF devices (and common to the world of industrial robotics) is that of "pivot point", where the known geometry of the mechanical stack of axis is combined with the inverse kinematic functionality of the motion controller to define a point in space (it could be the tip of a single fiber or a convenient point/feature of an active photonics element) that also takes into account the geometry of the gripper and of the device to be aligned.

An alternative to a stack of axis is presented in the paragraph that follows, though the adoption of these devices has been somewhat hampered mainly by the cost of these devices, and, sometimes by the limited travel range or by the robustness in the field.

14.3.1.2 Multi DoF/6 axis devices: hexapods and SpaceFabs (tripods)

The 6-DOF devices shown in Fig. 14.13 share a common concept: a top platform/flange that can be moved in an *X-Y-Z* space, including the rotation around these axes. These intrinsic 6-DOF devices are fully integrated with a dedicated controller that also provides the "pivot point" functionality and exhibits very good mechanical characteristics in terms of foot-print and compactness, overall accuracy, and stiffness.

Six legs/actuators are used in a Hexapod, while a SpaceFab can be considered a tripod, its three legs being moved by three *x-y* stages. Like their stack-of-axis counterparts, these devices are available in a range of sizes and payloads. The choice of one or the other is really application-specific, the authors having a slight penchant for the SpaceFabs, that have a squatter geometry and tend to merge better in the overall design of a machine.

Figure 14.13 A 6-DOF Hexapod and a SpaceFab. Not to scale.
Source: Courtesy of PI.

14.3.1.3 Motors/actuators, feedback sensors, and controllers

Electrical motors fall into two basic categories: stepper motors and servo-motors (the latter by now of the brush-less variety), selected for specific application requirements, such as speed and torque. Both types can be found in their linear form for the implementation of the long stages required by the geometry of gantry structures. A linear motor can be visualized as the "unrolling" of the stator and rotor of a conventional motor, thus transforming a torque into a direct linear translation. A feedback sensor—an encoder—is essential for the operation of a servo-motor, while a stepper can be operated also in open-loop, though in precision stages it is preferable to associate encoders also with stepper motors.

Piezo actuators differ substantially from conventional motors, and are based on the property of certain materials to convert an applied voltage to mechanical force. They are mostly used for short motion ranges with nanometers resolution, often combined with flexure-based stages.

Backlash and bi-directional repeatability, especially long-term effects, are the nightmares of stage designers. Encoders—the most common being incremental optical or magnetic encoders—exist in both rotary or linear versions, the latter being used to minimize the effect of backlash in precision stages.

Most piezo/flexure stages resort to capacitive sensors for both accuracy and dimensional constraints.

It is not uncommon to include external high accuracy positioning sensors when measuring distance or planarity, based on a variety of methods, from simple laser triangulation to white light or laser-based interferometry. It is interesting to note that photonics integration will also contribute dramatically to the cost and size of interferometry-based sensors, allowing their direct integration in the mechanical stages.

The generic name of "controller" is usually indicating both the positioning electronics (also known as indexing) and the power electronics driving the motors. Multi-axis interpolation and trajectory control is based on real time computation executed by an embedded computer, and application-level interfacing and programming is made easier by the presence of firmware interpreting and executing high level commands. Direct analog inputs and analog-digital converters facilitate active alignment and accept direct voltage signals from power meters or other detectors.

14.3.1.4 Conventional industrial robotics for pick and place

Industrial robots are extremely robust and reliable COTS (Commercial Off The Shelf) positioners with sufficient resolution, accuracy, and repeatability to solve a number of complex pick and place and other ancillary jobs, like epoxy dispensing and curing, in PICs assembly automation. They offer a very high degree of flexibility and can be easily reprogrammed for different tasks. Two different types of industrial robots are shown in Fig. 14.14. The small EPSON 6-axis C3 model with a payload of 1 kg (max payload is 3 kg) exhibits a repeatability of $\pm 20\ \mu m$ and a cycle time of 0.37 seconds, while the two Mitsubishi 4-axis, expressly designed for

Figure 14.14 A 6 axis EPSON C3 and two Mitsubishi parallel robots (see text).

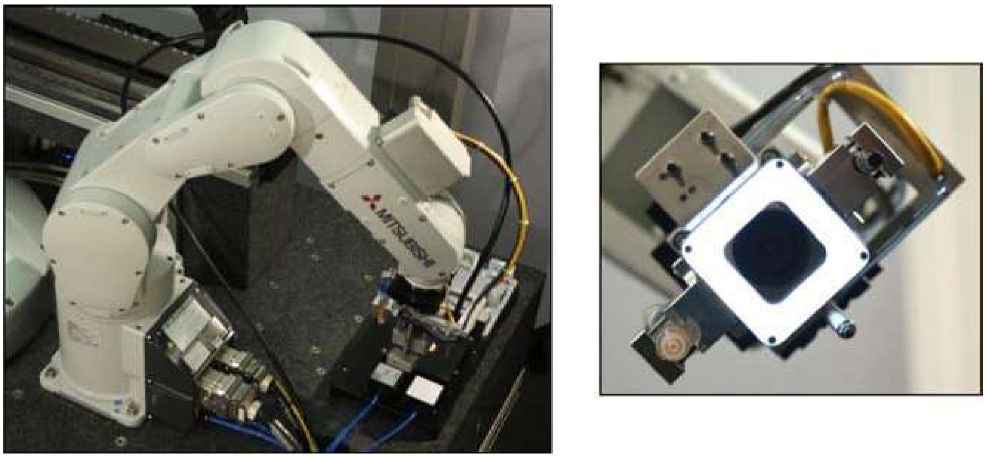

Figure 14.15 A 6 axis Mitsubishi robot and details showing the tilting multi-tool flange.
Source: Courtesy CNIT-Inphotec.

SMT and micro-electronics assembly offer a payload of 1 kg in a work-space of 150×105 mm with a repeatability of ± 5 μm and a cycle time of 0.28 seconds for the RP-1AH model, while this value becomes 210×148 mm, ± 8 μm, and 0.33 seconds for the RP-3AH version.

In terms of cost, industrial robot arms are highly competitive when compared with a conventional multi-axis configuration, and are available in "clean room" versions, complete with controller and high-level programming software. It is envisaged that more industrial robot will be engaged in fast pick and place in complete PICs assembly lines, where the transferring of the device being assembled across dedicated specific-function stations will also be required.

However, absolute accuracy is not sufficient for alignment tasks—either passive of active—and industrial robots should be seen as "ancillary" motion equipment in the context of PICs automated assembly. In Fig. 14.15 a 6-axis Mitsubishi robot can be seeing, with a multi-tool flange that can be tilted to load two different components, dispense epoxy, and perform UV curing.

Figure 14.16 A hefty granite optical table mounted in an enclosure with isolation support pads.

14.3.2 Optical grade tables and enclosures

All the mechanical positioning equipment has to be mounted and referenced to an optical-grade table surface. The most common platforms used are optical breadboards, with hollow honey-combed internal structure and pre-spaced tapped holes, or monolithic fine-grained granite slabs with tapped metal inserts, usually made-to-measure. While the breadboards are more suited to an experimental laboratory environment, granite is almost universally used for industry-grade automated machines. Passive or active vibration damping is used to support the optical tables, and this can be coupled with self-leveling functionality. An example is given in Fig. 14.16.

Granite, with a specific weight of approximately 3.000 kg/m^3 adds considerably to the overall weight of an automated assembly machine, and the typical weight of a granite table of a machine with an overall footprint of 2×1.5 m can easily exceed 1 ton.

Unlike laboratory equipment, fully automated assembly machines are completed with a fully closed outer enclosure with sliding or lifting doors. During operation the doors are closed and interlocked, also providing protection to the operators, in accordance with machine safety laws and regulations. Although designed for clean room use, the machine's enclosure can be completed with filter units and/or controlled atmosphere flow.

14.3.3 Bonding techniques and equipment

Once a specific component has been positioned and carefully aligned to the PIC substrate, some form of permanent fixing is required. A number of options are available and are listed below:

- Epoxy UV bonding, requiring accurate metering of the correct amount, dispensing to a precise location, and flash-curing by means of UV light. UV can be generated locally by means of UV LEDs, or conveyed by means of large diameter optical fibers connected to a UV source. Exposure time depends on the materials/devices being bonded, and whether they are transparent or not to the UV. Symmetric dispensing and curing is important, as well as epoxy shrinkage, to avoid unwanted displacement of the component being bonded, and active tracking is possible with the same equipment used for active alignment or other means of monitoring. A large variety of epoxy glues are available, with different optical properties, viscosity/fluidity, curing time, and shrinkage, together with different dispensing equipment, from metering pumps and needles, to bubble-jet type dispensing. Small uniform gaps between component and substrate ensure good epoxy distribution due to the capillary effect. Spurious dropping of epoxy, or blockages due to unwanted curing in the dispensing needles/nozzles are some of the worries of fully automated bonding cycles. Tens of seconds or even minutes are not uncommon in epoxy bonding processes (Fig. 14.17).

- Epoxy thermal bonding, is similar to the above, but relies on thermal transfer to start the epoxy curing. It requires local heating, usually resistive with a controlled electrical current, and thermal insulation to avoid thermal spreading and unwanted dilatation effect of surrounding equipment.
- Post-curing usually refers to the long-term stabilization of the epoxy bonding process, but it is usually done in batches heating up trays of components to moderate temperatures for rather long periods—could be hours—in off-line controlled ovens.
- Laser welding's main advantage is the short time required for this type of bonding, known for its long-term reliability and lack of outgassing as currently occurs from epoxies. It is usually confined to components with some metal-clad or metallic structures, such as metal-coated/metal-flanged fibers, alignment collects of TOSA/ROSA packages and the like. Using simultaneous symmetric welding reduces thermal displacement of the component to be welded, and it is illustrated in Fig. 14.18, a combined image that shows the 3D CAD drawing of the three laser beams, a self-leveling chuck, and a detailed of the welded ferrule. The small dimension of the welding spots and placement accuracy requires the use of machine-vision guided positioning equipment.
- Laser-induced soldering is particularly suited to complex multi-element assembly, especially when associated with flip-chip bonding. It can be easily extended to large area

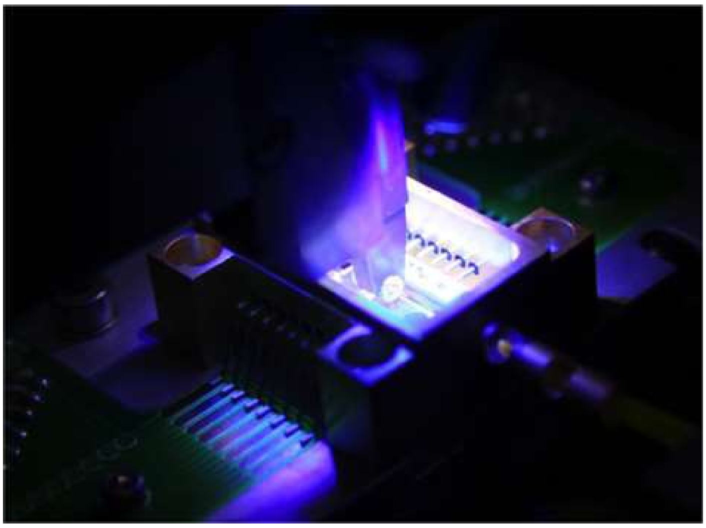

Figure 14.17 UV curing of a ferruled fiber inside a PIC butterfly package.

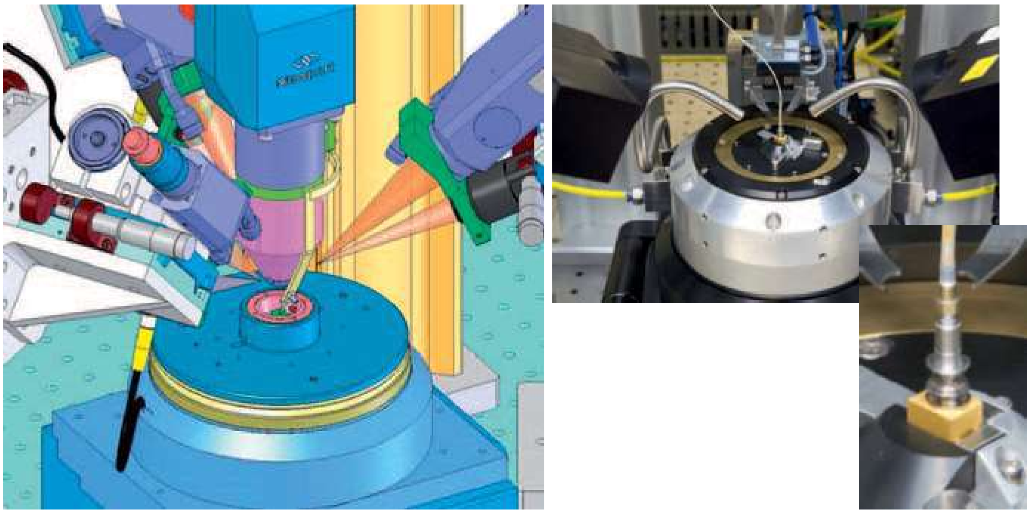

Figure 14.18 Simultaneous laser welding with three focused beams spaced 120° apart.

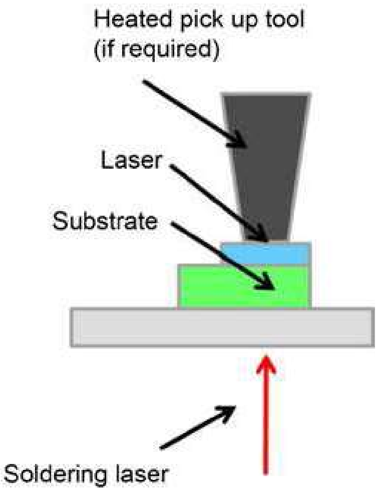

Figure 14.19 The principle of laser induced soldering.

substrates up to wafer level assemblies, as heating is applied only locally. It relies on positioning and focusing an IR laser beam via the back face of a silicon substrate/wafer to induce sufficient heating to melt previously dispensed pads of soldering alloys (Au/Sn, Ag/Sn, etc.). The associated equipment is known as fairly complex and expensive, but offers a high degree of flexibility and speed. Modern machine set ups can reduce this complexity by intelligent chuck design and software architecture (Fig. 14.19).

- Thermal compression bonding refers to a flip-chip interconnect technique, that uses micro-pillars or other micro-bumps, and relies on the application of heat and pressure to achieve simultaneous bonding of large arrays of these fine-pitch electrical contacts. Some 10–20 g of compressive force need to be applied for each bump, and the application of this technology for PICs automated assembly is limited to a limited number of interconnects. Full WLP (wafer level packaging) of wafers on wafers requires a massive amount of pressure and accurate thermal control over large areas, thus requiring the use of specialized machines.

14.3.4 Pickers, grippers, tweezers technology, electrical probing and chucks

An assembly process necessarily entails the picking/transport of a multitude of devices with different dimensions and characteristics, and delivery in a number of different packages, from pre-diced wafers to gel-packs. A PUT (pick-up-tool) is almost always "tipped" or terminated with one of these devices. A mixed list of devices/techniques follows:

- Vacuum pickers are the simplest devices, as they rely on a depression to pick up a device. While they can exercise a considerable vertical force, they are not suitable for large mechanical loads. Several vacuum nozzles can be combined to pick up larger devices, and top surface contact is normally required. Fig. 14.20 shows a vacuum picker in operation with a simultaneous ejector pushing upwards to facilitate the detachment of a small component from a blue-tape.
- Grippers or tweezers come in a variety of forms and sizes. They can be designed and implemented also for side gripping and to withstand higher loads than vacuum pickers. Actuation can make use of miniature pneumatic cylinders, electrical coils, miniature motors, piezo elements, or memory-effect metal alloy devices. An example of a gripper holding/aligning a $400 \times 200 \times 80$ μm lens in front of a laser emitter is given Fig. 14.21.
- A distinction is usually made between the actuators and their "fingers", the latter being usually interchangeable and designed for a specific component size and shape. Micromachining is often used to manufacture these mechanical elements.
- Vacuum pickers lend themselves to easily detect the presence/absence of a component, by simply measuring a vacuum/pressure level. Feedback on the operation of grippers and tweezers, including the actual position of the component being held, is usually provided via machine vision (via top, bottom, or side cameras). With the miniaturization of imaging sensors and the low cost of CMOS imagers and micro-optics, it will not be long before grippers are equipped with built-in cameras.

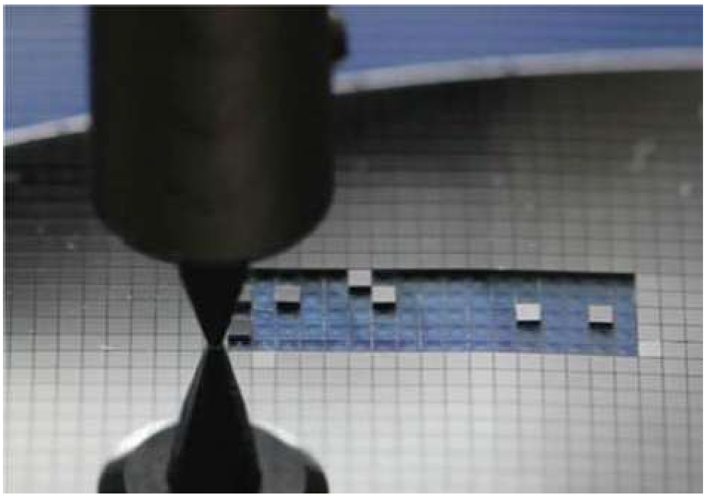

Figure 14.20 A vacuum picker lifting a 500×500 μm chip from a pre-diced wafer on blue-tape.

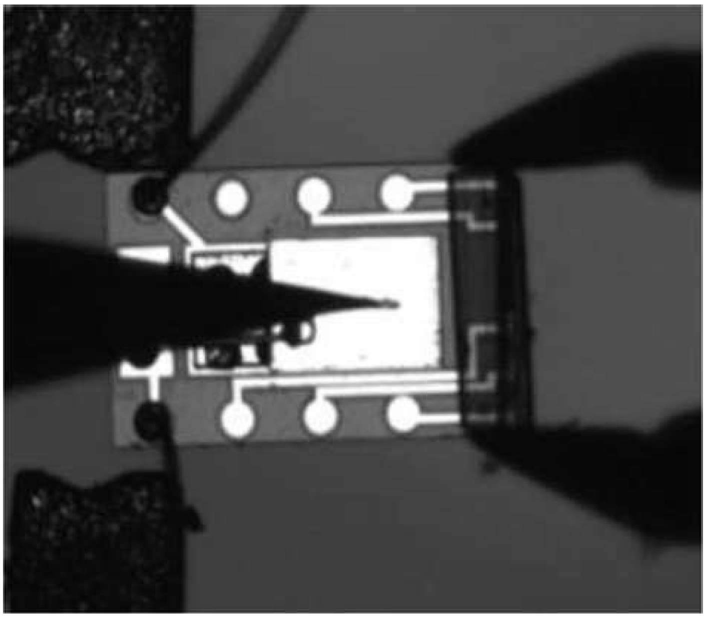

Figure 14.21 A gripper holding/aligning a micro lens in front of a laser emitter.

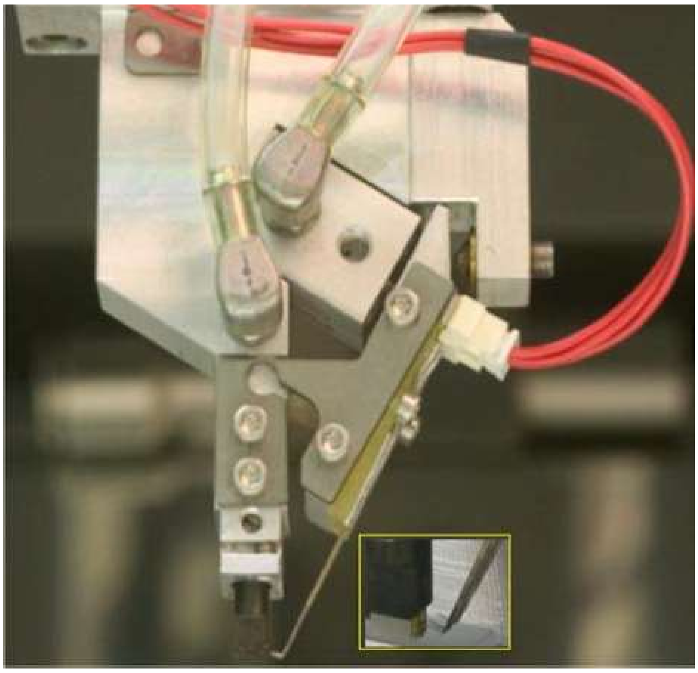

Figure 14.22 Electrical probing of active components.

- Electrical probing of photonics devices, such as laser diodes or photo-detectors, is required for active alignment, and grippers need to be equipped with electrical probing contacts, as shown in Fig. 14.22.
- Complex, multi-element PICs assembly processes require the rapid interchangeability of pick up tools. This is achieved by standardized flanges that are equipped with

pneumatic, vacuum, and electrical connections, and are also designed for accurate mechanical locking. Different tools can be housed in a "carousel" and exchanged automatically.

- Pick up tools and probes are by necessity based on rather fragile mechanical structures and are subject to a degree of "wear and tear", as well as being the first casualties of the operator's errors in the commissioning and programming of the machine sequence of operations. Field interchangeable spares are usually supplied to the end users.

The photonic device being assembled and completed with a number of different active or passive optical components is itself held in what is commonly termed a "chuck". Again, the chuck design and size are specific for a given component, and almost invariably are interchangeable to guarantee flexible operation of the assembly machine.

While all the different elements described above do not represent the highest complexity and cost of the whole machine, they occupy a key position in its continuous and successful automated operation. A refined and detailed know-how of both mechanical design and material selection, including surface treatment and hardening, of these tiny machine parts is essential, and can have a considerable impact on the overall assembly equipment up-time.

14.4 Machine vision

Machine vision has already been mentioned in the context of passive/active alignment, but it is also used for a variety of other tasks and it represent an essential part of an assembly machine. It is ubiquitously found in pick and place operations, positioning and alignment of parts, automated optical inspection, parts identification via OCR (optical character recognition), and code reading, as well as beam characterization, both in the visible and in the IR range.

Cameras have been used as visual aids since the early days of photonics packaging, but purely to display enlarged images of the devices being manipulated and assembled. Machine vision refers instead to the use of image processing algorithms to automatically extract features and information from an acquired image. In most instances, this information is then correlated to motion equipment positional data and exploited to perform automated operations.

These few paragraphs are not sufficient to provide a "primer" on machine vision for PICs assembly, but a few concepts and examples are given, with the help when appropriate of a few images (it would be difficult to discuss machine vision without images!).

The image in Fig. 14.23 dates back to 2001, and was acquired with a digital camera of 1300×1030 pixel resolution and 8-bit dynamic range (then state-of-the-art), but it exhibits both poor contrast, possibly due to a bad illumination, and poor focusing. Nevertheless, the edge-detection based algorithm correctly identifies the edges of the V-groove, the outer circumference of the fiber and its center, and the red dot

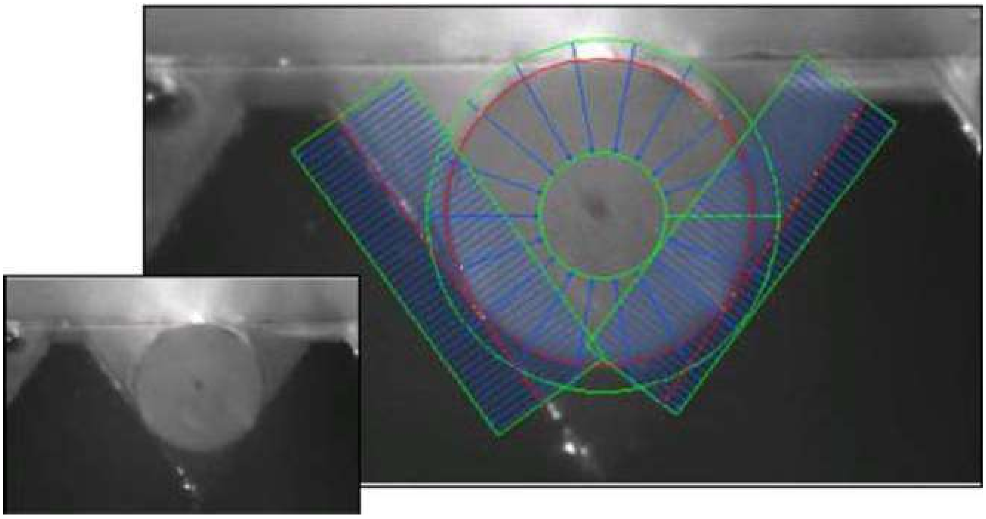

Figure 14.23 A digital camera image (from 2001) of a FO epoxied in a V-groove.

that lies within the "smudge" that corresponds to the mono-mode fiber. A colored overlay graphic helps the user to understand how the image processing is performed:

- The two green rectangles and the green annulus define three ROIs (Region Of Interest) where the image processing is applied.
- The blue lines show where an edge-detection algorithm (a function that looks at pixel intensity variations along a line) is repetitively performed.
- The red overlays show the identified results: the left and right edge of the groove, and the circumference and center of the fiber.

The same image can be used to introduce one of the major limits of machine vision in photonics assembly automation: optical resolution. The image was acquired with a resolution of approximately 0.32 μ/pixel and covers a FOV (field of view) of 968 × 656 pixel, corresponding to an area of 0.312 × 0.211 mm. This is further illustrated in Fig. 14.24, which shows the image of a 10 μm/line reticule on a glass plate, acquired via a Leitz microscope with a 20 × objective and 1.25 × relay lens on the same digital camera. A loss of sharpness and some artifacts (a "shadow" on the right of each line) are noticeable. The intensity of each pixel along the line in the zoomed image is plotted in the "line profile" graph. The distance between two adjacent peaks is approximately 40 pixels, corresponding to 250 nm/pixel. A better concept in terms of image quality is that of MTF (Modulation Transfer Function) that combines both spatial resolution and image contrast.

It can be seen in the line profile plot that out of the 8-bit dynamic range (255 levels) only about 1/3 is actually used.

In practical use the overall quality of the lenses, the illumination that can be implemented, the actual morphology of the markers and features we can find on a photonics chip, and the need to have reasonably large FOVs make it difficult to go below 1 μm or 0.5 μm/pixel resolution.

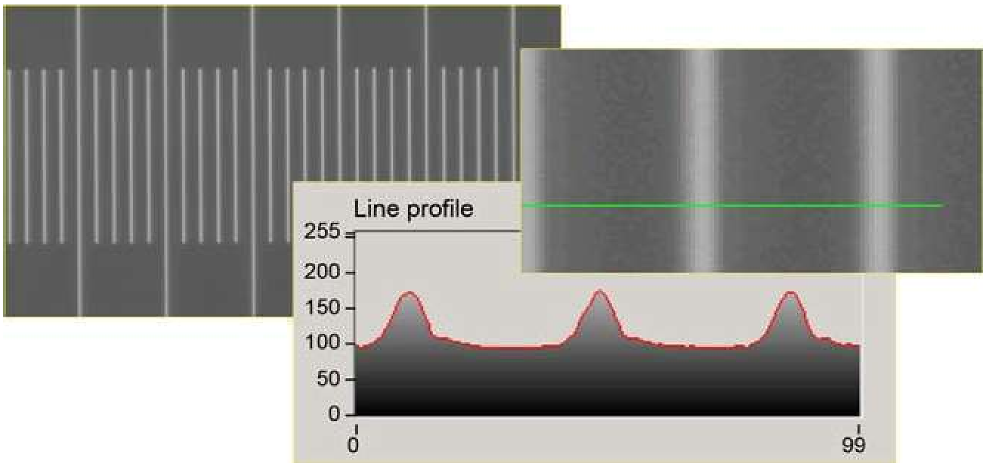

Figure 14.24 Onset of diffraction limits and MTF.

Large sensors are now available and a 29 Mpixel (with 6576 × 4384 pixel sensors) camera's cost is today approximately half of that of a 1 Mpixel camera in 2001, and allows acquisition of a full 6.5 × 4.3 mm area with a 1 μm/pixel resolution. This would greatly reduce the need to move the camera and allow the use of a single focal lens (zoomable lenses are not of great use in photonics assembly as they have poor optical/mechanical stability). Sub-sampling, selective ROI, and software zooming and panning can be used to minimize the amount of acquired data.

Although imaging algorithms can be developed from scratch, and ample literature, dedicated "recipe cook-books", and free software sources are available, it is felt that robust, well documented, and extensive image processing libraries are available on the market from several reputable vendors, and this should be the preferred choice in the implementation of industry-grade assembly equipment.

Combining imaging and motion also requires the correlation of the dimensionless world of pixels with that of the mechanical axis and their accurate encoders. These might include also the relative calibration of separate top and bottom cameras, often used in flip-chip type of components placement and other alignment routines. Dedicated calibration targets are required, either fixed or inserted into the cameras optical paths when required. Automated software calibration routines are than executed and can be repeated during machine commissioning, periodically, or whenever maintenance requires it. In the set up of Fig. 14.25 a top and bottom camera calibrated with the motion equipment also allow for correction of misalignment after picking.

Calibration procedures and other guiding/alignment algorithms can also be based on markers purposefully etched on the photonic chip to be assembled; aligned or exploiting geometric features already existing that are intrinsically accurate, being based on the lithography masks of the chip foundry processes. An example is given in Fig. 14.26, where a multiple grating structure provides alignment information for a v-groove fiber array. The optical connection between the outer ports provides angular correction along the major axis of the array, while the geometry of a single

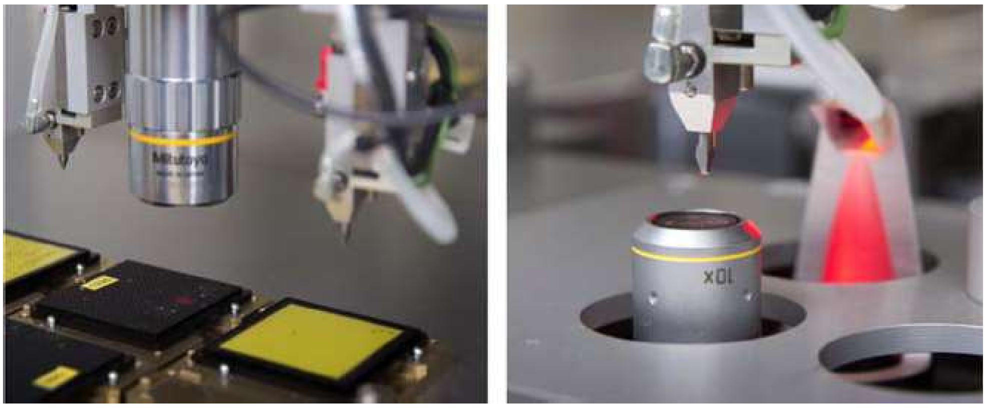

Figure 14.25 A top–bottom camera set up.
Source: Courtesy of ficonTEC GmbH.

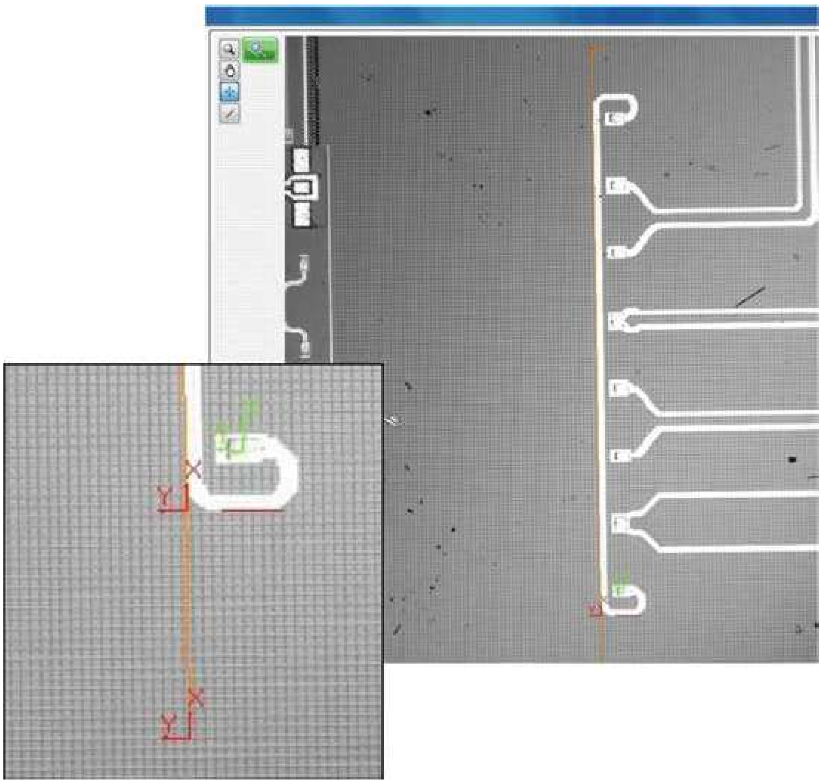

Figure 14.26 Using on chip existing features.
Source: Courtesy of ImagingLab/ST Microelectronics.

grating provides the coordinates that ensure "first light" for successive active alignment. The outer port connection is effectively an optical short circuit that allows the use of an external laser source and an external power meter to perform the active alignment.

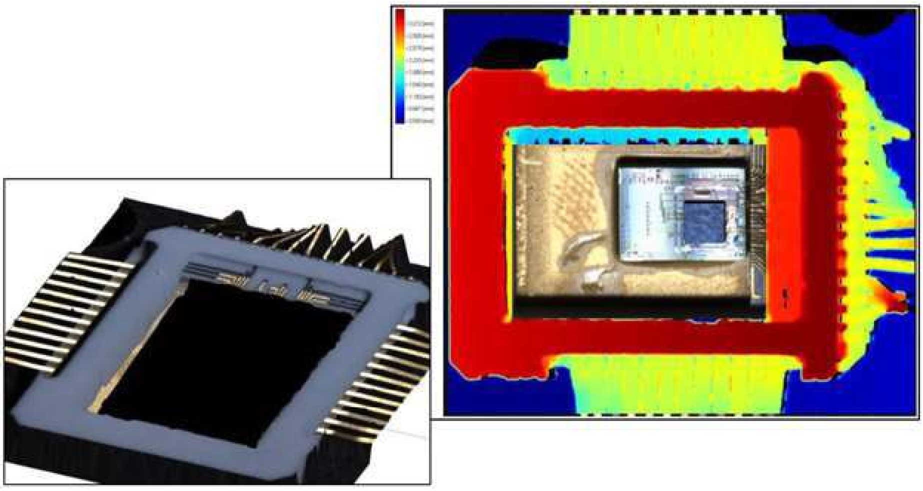

Figure 14.27 A 3D image of a photonics chip with a calibrated Z-scale.

To conclude this section of the chapter, a few words will be spent on 2D versus 3D imaging. The images shown above, and indeed most of the imaging that is today used in assembly equipment, is based on gray-scale 2D imaging. Assembly is essentially a 3D process and would certainly benefit from 3D machine vision. The *X*-*Y* matrix of intensity values in 2D imaging is replaced in a 3D image by a COP (cloud of points), where each point represents a triplet of *X*-*Y*-*Z* values in space. Three-dimensional cameras with sufficient *Z* axis resolution are not yet widely available, especially when speed and cost are taken into account, but different techniques are being developed, together with the corresponding software for 3D data processing.

A 3D test image acquired with a fast line scan camera and based on autocorrelation methods is given in Fig. 14.27: the false-color scale of the right-most image is actually a calibrated *Z* measurement.

14.5 The role of software and HMI in the optimization of new processes

Complex machines like the one outlined in the previous paragraphs can only be operated via a massive amount of software, and it is ultimately the software that qualifies and determine the success of a new piece of assembly equipment on the factory floor.

The role and main tasks of the machine application specific software can be briefly explained as follows:

- Provides a functional and user friendly HMI (Human Machine Interface) with a modern GUI (Graphical User Interface), hiding the underlying complexity of the machines, and possibly separating different classes of users, from the operator on the factory floor, to the process engineer responsible to configure a complete packaging production sequence.

- Allows all the parameters of a complex assembly to be described and set in a sequence of individual steps that can be individually tested/debugged prior to a fully-automated production cycle.
- Accommodates easily all the inevitable changes that will occur during the development/optimization phase of a new PIC packaging process.
- Allows semi-automated operation when operator intervention/checks are required in the initial ramp-up to production of new or unfamiliar PIC devices.
- Generates editable "recipes" to allow the automated packaging of "families" of PIC devices.
- Provides also an easy user interface to advanced machine vision, hiding complex image processing algorithms tuning via simple parameter settings and clear visual image overlays.
- Provides interface access to a wide pallet of test and measurement instruments, whether they are delivered together with the machine or added at a later stage.
- Allows quick re-tooling of the pick-up end effectors and handling equipment, and accommodates hardware changes, possibly with automated calibration procedures, to preserve the capital equipment investment over time.
- Provides production data down to the single assembled device and interface to the manufacturers databases for yields and production monitoring.
- Provides self-diagnosing/power-up tests when the machine has to undergo a "cold start".
- Allows remote connection (under end user control) for both remote maintenance/support, and for remote software upgrades.

It is likely that a machine manufacturer will use a collection of different software programming environments for different parts of the machine (like C, C++, Python, LabVIEW, etc.) to program the motion control subsystem, off-the-shelf machine vision libraries, specific graphical user interface development tools, etc. As long as the various software elements are well integrated and seamlessly presented via the HMI interface, this should not constitute a worry for the end user. It is likely that the machine will be run with a conventional PC, either in a conventional or industrial ruggedized form, and it should similarly be possible to mix both real time operating systems and conventional OS (like MS Windows).

The key issue is that the end user should not need to provide any programming efforts or skills, but only learn how to configure the machine to optimize a given process, as well as integrating the machine in the IT infrastructure of the manufacturing plant if/when required.

A recurring discussion is also on whether the software provided with the machine should be given in a closed (run-time/executable only) or in an open (access to source code) form. Opening the software to the end user carries two major problems: first, the manufacturer is liable for the correct functioning of the machine, expected life time of the major components, safety of operation, etc., and this is highly dependent on the software implementation, and second, a lot of intellectual property is built in/accumulated in the machine software. An easier way out is to provide a specific high-level interface layer that allows the end user to add specific software "tools" at HMI level, via a defined protocol for handshaking and variables exchange. This specific point should perhaps have been added to the list at the beginning of the paragraph.

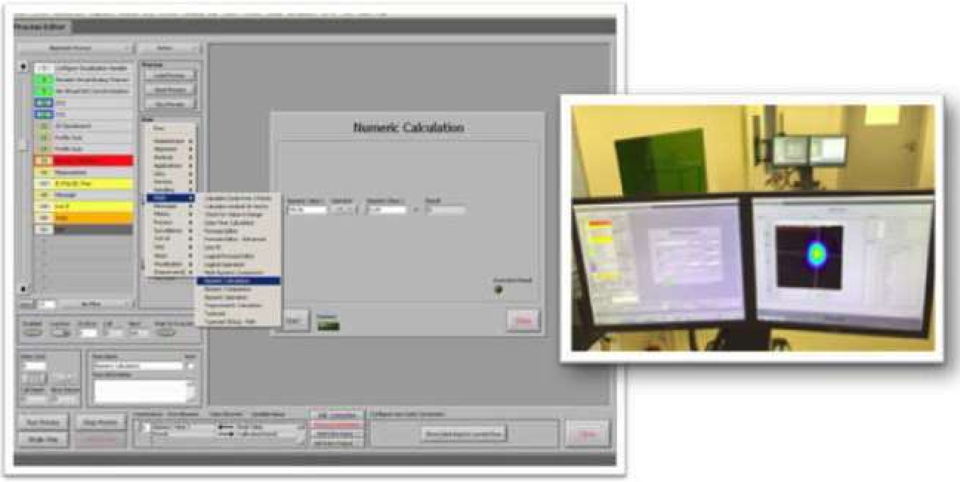

Figure 14.28 A high-level HMI interface developed at ficonTEC.

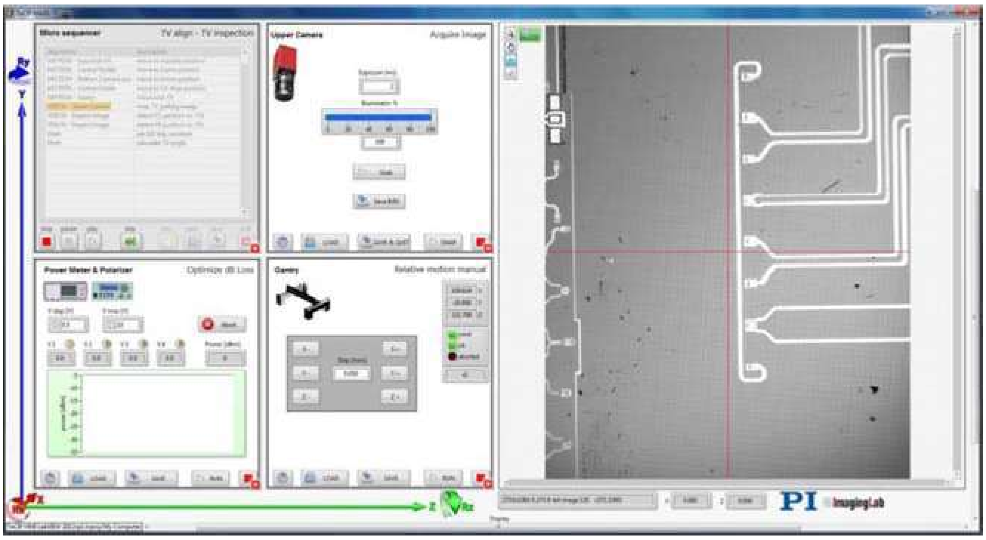

Figure 14.29 A high-level HMI interface developed by ImagingLab for PI.

Interestingly, the two examples of HMI software interfaces provided in Figs. 14.28 and 14.29, and developed separately by two different manufacturers, share most of the concepts just outlined and are both based on LabVIEW.

14.6 Test and measurement instrumentation

As the assembly of PICs often entails different kinds of measurements (voltages, currents, temperatures, light intensity and power, light frequency, beam characteristics, monitoring of laser sources, RF measurements, etc.) the integration of a vast array of instrumentation is also required. Full characterization of a PIC device is

Figure 14.30 A PXI-based data acquisition system compared to a stack of conventional instruments.

usually performed off-line, requiring dedicated and expensive instrumentation. The testing required for assembly is better referred as in-line testing, and might not require the same class of instrumentation. A distinction can also be made between conventional "rack and stack" instruments and more compact data acquisition systems, offering also a lower foot-print in a clean room environment, as well as likely cost reductions, with a comparison given in Fig. 14.30.

The instrumentation cost issue will become more apparent with the increase in PIC manufacturing volumes, and might well lead to the development of specific low-cost modules targeting optical measurements but exploiting multi-vendor standards like PXI.

In both software application/HMI examples given in Section 14.5, software interfacing is included at a high level, and is performed via an open interface using LabVIEW (a trademark of National Instruments), almost a de facto standard also adopted in semiconductor and other electronics manufacturing industries. Most instrument vendors offer free interface software, referred as "drivers", that is LabVIEW compatible. This facilitates both the instrumentation integration during machine assembly and production, as well as later on at the customer premises.

14.7 Design for automated assembly/testing and standardization

Photonics packaging is still at a rather early stage, with a number of technologies being studied and developed to reduce its complexity and cost. It is also characterized by a remarkable lack of standards, and while the two things just mentioned are certainly related, some easy steps could also be discussed and implemented, and few are listed:

- Define some preferential layout whereby electrical and optical interconnect ports occupy specific sides and chip area.
- Define classes of sizes, as this will reduce the number of different chucks, grippers, and various holders, and thus cost, of the assembly machines.

- Remember that the placement and spacing of discrete components like laser sources, CoS (chip on sub-mount) components, and free-space micro-optics elements might require some physical space for the pickers to maneuver; the same is valid for dispensing glue.
- Keep these devices away from wire-bonding areas if they need to be assembled after wire-bonding.
- Avoid high-walled bath-tub types of packaging, as it makes it more difficult to enter the package with grippers and probes (electrical and optical).

The list could continue, but what is really required is better communication among all the players in the long chain of PICs manufacturing, starting from the providers of photonics design tools all the way to wafer production and packaging process experts, keeping the assembly equipment manufacturers in the loop also.

14.8 Automated testing

Reworking during the assembly of a complex PIC layout is almost impossible, and even when it is would require costly manual intervention. Testing is therefore required in-line (i.e., during assembly) and off-line, at either single die, bar, or full wafer level.

A broad distinction can already be made for devices adopting top grating coupling and those adopting edge coupling, the latter requiring either dicing before testing or some other approaches, like etching or cutting trenches in order to reach the edge coupling structures. A couple of novel technologies are being explored at the University of Southampton, UK [7], and at the Polytechnic of Milan, Italy [8], and more might be in progress not known to the authors.

Full wafer-level testing will require some creative approaches to mixing electrical probing and optical probing in a fast and cost-effective manner.

A distinction could also be made between full characterization and expensive, top-class instrumentation, and that dedicated to in-line testing during assembly and/or full wafer-level testing. For the latter, some low-cost modular optical instrumentation front-end, possibly adopting existing test and measurements platforms, has not yet emerged.

14.9 Conclusions

A more detailed description of the processes and the machines dedicated to PICs automated assembly would probably require a full book rather than a single chapter, but it is hoped that a good and sufficiently clear overview was provided in the preceding paragraphs. It is felt that more work will be required to link the design of PICs devices to full volume manufacturing processes, and that growing volumes will also promote changes in the design of the machines. Some of today’s flexibility will probably be sacrificed for speed, and full production lines will be based on a number of simplified and single-task stations, with some parallelism from the slower steps of the full assembly process. Shuffling partially assembled devices and handling all the incoming parts could be done by robotics arms, and much shorter fiber ribbons in some standardized delivery packaging will have to be devised to allow fully automated loading/unloading. Machine manufacturers will need to monitor advances in micro-optics and multi-port miniaturized optical connectors, that could greatly simplify fibers pig-tailing, and, at least partially, remove some active alignment requirements. The increase in volumes, and hence more investment in capital equipment and multiple machines single purchases, will also allow machine manufacturers to allocate some NRE (Non Recurrent Engineering) efforts to reduce costs and speed up production cycles.

Plenty of automation is already available today adopting best-in-class equipment and technologies, also borrowing existing concepts from adjacent large-volume manufacturing industrial segments.

A number of changes are likely to occur, and adaption to these changes will be essential for both PICs manufacturing companies and machine suppliers.

To conclude with few words for all those involved in PICs packaging: design for automated assembly, design for testing, design for speed of both assembly and testing, and minimize/limit packaging differences by promoting standards!

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