2.1 Modular Microoptical Systems for Sensors and Telecommunication

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Abstract

This paper focuses on fabrication and assembly processes of modular and hybrid microoptical systems in use in sensor and telecommunication fields. These microoptical systems are made by a huge variety of processes, which are commonly known as microsystem technology. Nevertheless, quite a lot of them are based on the LIGA process, since LIGA is an "assembly friendly" technology.

Modular microoptical systems typically comprise several functions incorporating mechanical or electromechanical components beside the optical elements. The assembly of the diverse submounts and components is performed actively as well as passively. In many cases, all of these functions can be combined on one single chip. In several cases, however, a pair of chips, which is assembled in a flip-chip like way, is used.

The framework of the paper leads to a definition of the terminus "modular microoptical system" and argues for the advantages of such a modular design approach. It closes with some remarks on automatic assembly strategies.

Keywords: microoptics; modular; hybrid; flip-chip; assembly

Contents

2.1.1 Introduction

The tremendous increase in demand for rapid information and communication has pushed light to the number one data transfer medium. The great advantages of light are not only its unique velocity but also its insensitivity to disturbance because the photons do not interact either with external fields or with themselves. This makes light a very attractive medium to transfer information, especially across long distances but also on short stretches. The percentage of information that is already transferred by light through optical fiber networks differs from country to country. In Germany, for example, it has already reached 90% since investigations started quite early in this promising technology [1]. Recent interest in optical telecommunications lies not only in global networks, but also in private households [2] and in cars [3]. Hence optical components that enter the consumer market are subject to increased price pressure.

Similar arguments are valid for optical sensors. Again, the insensitivity to disturbance is the main reason for the increasing application of optical sensors in cars and industrial production for control and monitoring of automatic processes. Also in medical technology, optical sensors are of great interest because they are mostly non-invasive and can be used in the proximity of strong fields, eg, close to the magnetic field of a nuclear resonance tomograph [4].

Striving for cost reduction through higher integration and on-going miniaturization, the field of micro optics becomes an enabling technology for optical telecommunication and sensors. There are two basic technology approaches: a fully integrated fabrication sequence or a modular or hybrid set-up. The choice of which one is the most suitable is related to the number of pieces to be fabricated, the complexity of available processes and the respective yield, and the freedom in design and construction. Each approach has its specific advantages. In case of lower numbers and for the combination of several functional components, the modular design and fabrication is often the better choice. The processes are easier and safer, and one can work with pre-tested components, which helps to enhance the yield.

This chapter concentrates on micro optical systems for telecommunication and sensors that follow the modular approach, in addition based on micro electro mechanical system (MEMS) or micro opto electro mechanical system (MOEMS) techniques. Examples for diverse purposes will be presented.

2.1.2 Definition of a Modular Microoptical System

The definition of the expression 'modular microoptical system' as it will be understood in this paper is best done in the reverse direction. An 'optical system' comprises a variety of functions in one unit: optical function and normally electrical and/or mechanical function. Examples of pure optical function are simply light transfer, refraction and diffraction, imaging, filtering, light splitting or superposition. Electrical or optoelectrical function can be light generation, detection or analysis, electronic circuitry, or current/voltage supply to other functional components. Mechanical or electromechanical function is provided by alignment structures or positioning aids, fixing and clamping structures, actuators, heaters and coolers.

Such an optical system is called 'micro' when at least one component of it is fabricated by means of micro-technology. The overall size of the system or even of the diverse components is not necessarily in the range of micrometers, but maybe some structural detail calls for micro-technology. A huge variety of such microoptical systems have been presented in recent years. These can simply be fiber couplers [5] or beam splitters [6], or more complex devices as switchable mirrors [7, 8], fiber switches [9, 10], Fabry-Perrot interferometers [11], or modulators [12].

A microoptical system is defined as 'modular' or sometimes just 'hybrid' if the diverse functions are not fabricated in one common fully integrated fabrication sequence and/or if they are not integrated on the same substrate. An optical bench, eg, fabricated with an adapted process on one substrate, and an actuator, which is fabricated with another specific process on a second substrate, form two modules, which are finally put together. In addition, the components required for each module can be fabricated separately and mounted in a hybrid way. It is clear that the definition of 'modular' and 'hybrid' cannot be used rigidly. In general, the individual scientist decides whether he or she considers a system just developed already to be a modular or just a hybrid set-up. Also in this chapter, we did not succeed in separating them. Hence modular and hybrid systems will necessarily be mixed up or even lead to contradictory points of view. We will stress this aspect in Section 2.1.5, which describes the most complex modular systems in this chapter.

Anyhow, no matter what name it is given, a modular or hybrid microoptical system is always related to assembly technology comprising alignment and fixation [13]. This can be performed either actively or passively. Active alignment means that the output signal of the system is monitored during assembly in order to obtain an optimum result. Passive assembly, in contrast, makes use of integrated alignment aids for the diverse components without the need for monitoring. The question of which method is the most suitable needs to be answered for each system separately. It is dependent on the function of the system and on the available fabrication and assembly procedures.

The examples of modular microoptical systems that are given in the following sections are split into three categories. The first covers pure opto-*mechanical* systems without any need for electrical units. The second covers opto-*electro*-mechanical systems in which the electrical units are responsible for light generation and detection. The third also describes opto-electro-mechanical systems, but including electrically driven actuators. In order not to overload this chapter, only the modular concepts and operating principles of the systems will be explained. For detailed results we refer to the original publications.

2.1.3 Optomechanical Systems

Pure optomechanical modular systems can hardly be found. Again, the boundary between a monolithic, integrated system and a hybrid, modular system is floating. This becomes clear from consideration of an optical bench with non-integrated but assembled microoptical components. The base plate of an optical bench mostly is a monolithic device with alignment aids and perhaps some integrated devices such as a prism or a mirror. When additional components such as fibers, lenses, beam splitters, etc., are assembled on the bench it becomes a system according to the definition above. A very simple example is a fiber coupler as used for telecommunication purposes with the optical function of guiding light from one fiber to the next and the mechanical function of alignment and fixation. Three different approaches to fiber couplers are presented in the following discussion.

2.1.3.1 Fiber Coupler in Silicon with Rhombus-like Grooves

Fibers are commonly aligned by grooves on a chip running parallel to the fiber axis or they are pushed through holes in a chip mounted perpendicular to the fiber axis. Most popular are V-grooves etched in single crystal silicon [14]. The fibers are fixed by glue and covered with a glass plate. A newer approach is to use rhombus-shaped channels [15] as indicated in Figure 2.1.1. The grooves allow for lateral and vertical positioning of the fibers. The authors claim two advantages over simple V-grooves. First, the volume of the rhombus is smaller, thus reducing the amount of glue which is necessary. This again reduces shear stress in the whole assembly of the Si chip, the cover glass plate, the fibers, and the glue owing to the different thermal expansion when temperature changes occur. Second, fiber assembly is very easy because funnels are generated owing to the etching process at the edges of the chip. The fibers are inserted at the wide end

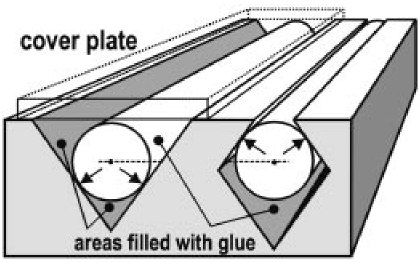


Figure 2.1.1. Comparison of fiber grooves with triangular and rhombus-like shapes [15] (with permission of Springer-Verlag).

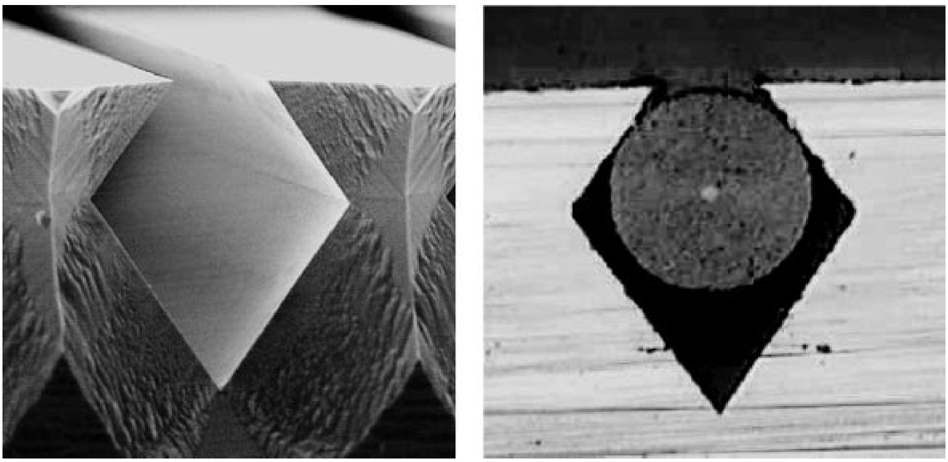


Figure 2.1.2. Rhombus-like channel with funnel at the end etched in silicon and fiber assembled in channel [15] (with permission of Springer-Verlag).

of the funnels, and as they are pushed forward they center by themselves (Figure 2.1.2). The end face is finally prepared with a wafer saw.

2.1.3.2 Easy-assembly Fiber Coupler from Polymer

A coupler with longitudinal grooves for 16 multimode fibers is described in [16], and is illustrated schematically in Figure 2.1.3. It consists of two plastic pieces made from poly(methyl methacrylate) (PMMA): one for the alignment of fibers and guide pins with five rows of highly precise alignment structures, and the other for their fixation and protection. Elastic ripples in the side walls of the alignment structures, as can be seen in a scanning electron microscope (SEM) photograph in Figure 2.1.4, facilitate fiber and pin insertion. They also make the connector insensitive to variations in fiber diameter. The gap between the alignment structures decreases successively from the last row to the first row facing the opposite connector. This permits very easy assembly and passive alignment of the fibers without the need for micro-positioning. Since the gap at the front face is 2 μm smaller than the fiber diameter, the fibers are clamped gently by the alignment structures, thus allowing easy handling during the on-going assembly. To bond both parts, UV-curing adhesive is filled into the device through a hole in the upper substrate. The glue spreads into the coupler just by capillary forces. Finally, the front face is polished. The pins of both connectors to be coupled are inserted into a highly precise coupling adapter as indicated in Figure 2.1.5. If the pins damage the respective holes in the adaptor owing to repeated reconnection, the adaptor can be replaced easily whereas the fibers and connectors can be maintained. The coupler is fabricated by means of plastic micro-injection molding made from PMMA. The respective molding tool was fabricated by LIGA technology and micro-precision engineering as described in detail in [16].

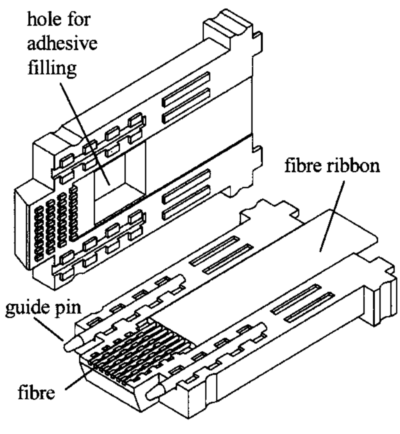


Figure 2.1.3. Schematic of ferrule.

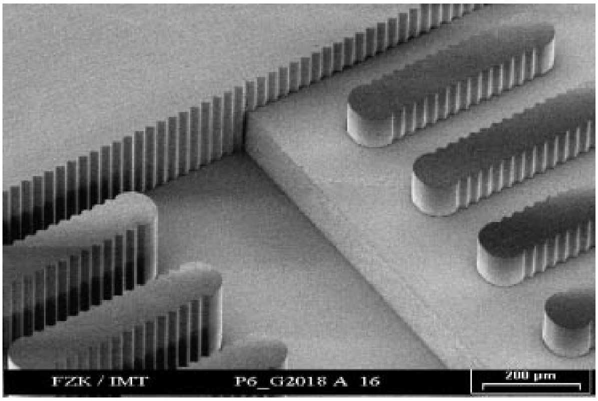


Figure 2.1.4. SEM of alignment structures.

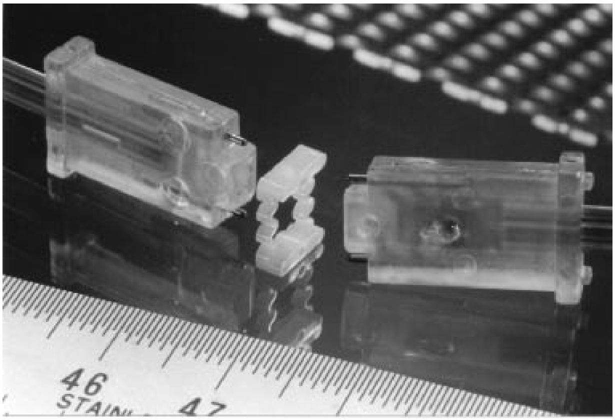


Figure 2.1.5. Pair of ferrules with coupling adapter.

2.1.3.3 Expanded Beam Fiber Coupler

A comparable connector concept is reported in [17]. The authors also describe an injection molded coupler for which the tool was made in a similar way; however, the precision fiber grooves are obtained by V-grooves etched in silicon. They extended this concept to an expanded beam coupler [18] with the advantage of decreased sensitivity to fiber misalignment and to impurities. In that case the fibers are not coupled face to face but lens arrays are placed between them in order to expand the light beam for coupling and refocus it again into the output fibers as sketched in Figure 2.1.6. For this purpose, lens alignment structures are positioned in front of the V-grooves. Figure 2.1.7 shows the front face of

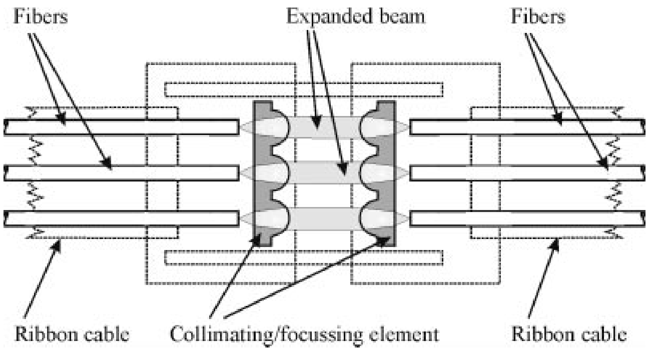


Figure 2.1.6. Principle of an expanded beam fiber coupler [18] (with permission of SPIE).

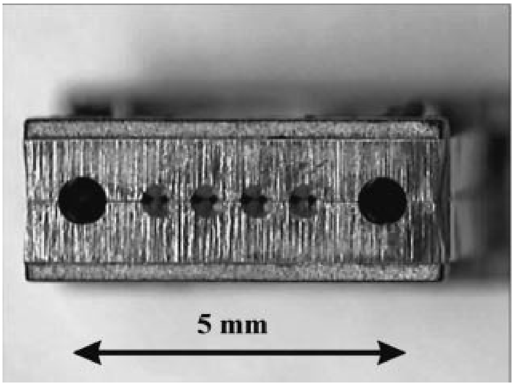
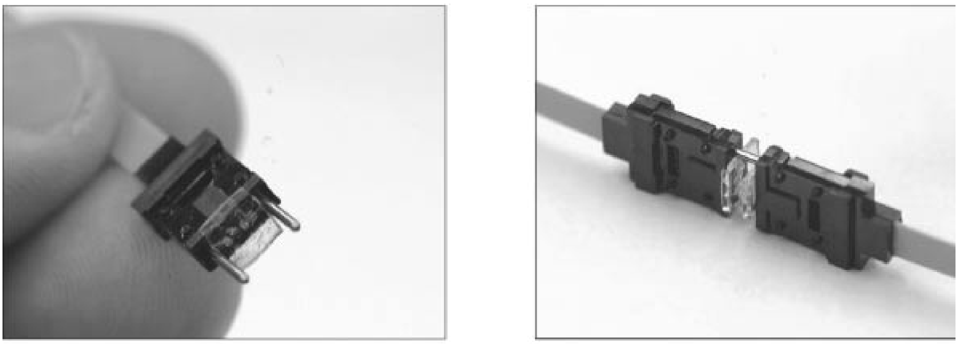


Figure 2.1.7. Front view of a molded expanded beam coupler with alignment structures for a lens array [18] (with permission of SPIE).



(a) (b)

Figure 2.1.8. Assembled coupler with lens array, guide pins, and fiber ribbon [18] (with permission of SPIE).

such a micro-molded coupler. The four smaller circular holes are the place holders for the lenses and the two bigger holes for the guide pins. The coupler is equipped with fiber ribbon, a lens array of 500 μm diameter lenses and guide pins as shown in Figure 2.1.8.

2.1.4 Opto-electromechanical Systems 1: Optical Benches Combined with Electrooptical Components

The combination of electrooptical functions given by light sources and detectors with optical benches as described above follows more the idea of a microoptical *system*. The totally different purposes of opto mechanics and opto electronics call for a modular approach since the integration of all functions on a monolithic substrate makes processes very complex, difficult, and expensive. Thus, examples of this category of modular microoptical systems are found in a larger variety. Nevertheless, reviewing the literature one finds that this field is dominated by LIGA-made systems. This may be related to the fact that, on the one hand, thick microstructures are helpful for alignment, and on the other hand, groups working on silicon processes and optical lithography tend to look for a higher integration level. Therefore, we present three systems made by the LIGA technique but close this section with a sensor system made by silicon micromachining and optical lithography.

2.1.4.1 Heterodyne Receiver

Figure 2.1.9 shows the set-up of a heterodyne receiver, ie, a wavelength filter for telecommunication. In this case, two incoming light beams need to be split and superposed again [19]. The signal light and the light from a local laser are coupled into the system by means of monomode fibers. The light is collimated by ball lenses and then split into its two polarization states. Reaching the next optical surface, the beam of each polarization state is again split by 50% and is simultaneously superposed with the respective beam from the opposite light source. Each of the final four superposed beams is detected by a photodiode. The system consists of a ceramic chip on which alignment structures from the polymer are patterned using LIGA technology. The fibers, the ball lenses, the prisms for the beam splitters, and the diodes are separately manufactured components, which are assembled in a fully passive way on the chip. They are just pushed towards the alignment structures and fixed with some UV-curing glue. The accuracy is of the order of 1 μm. Since the altitude of the optical axis is defined by the diameter of the ball lens (here

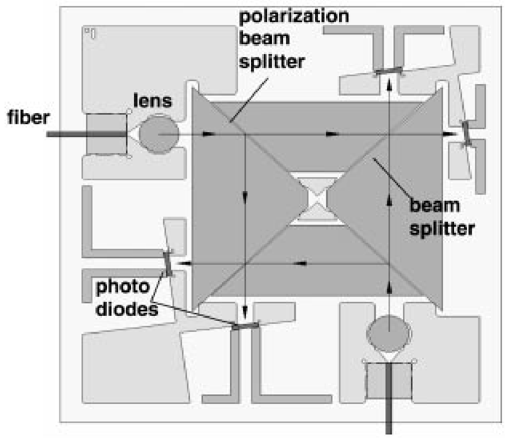


Figure 2.1.9. Set-up of heterodyne receiver.

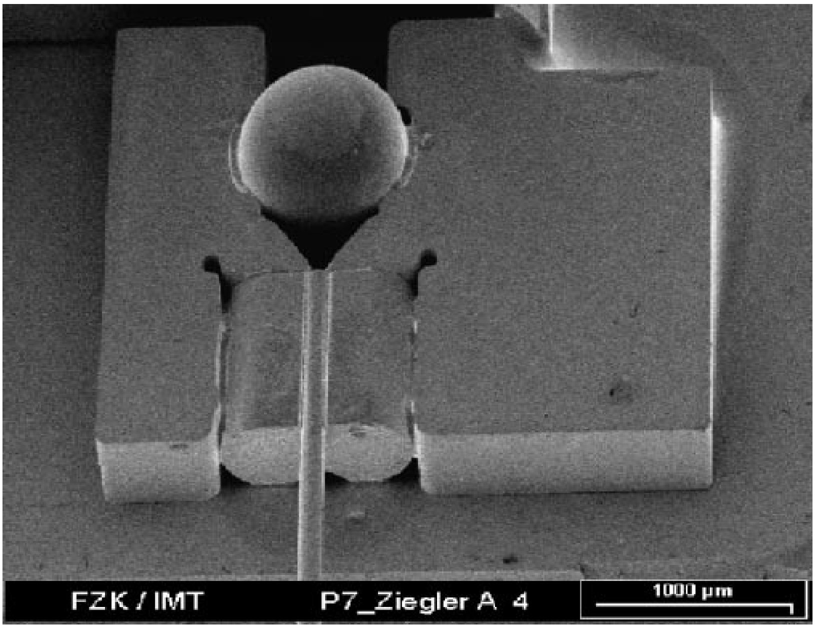


Figure 2.1.10. Fiber mount levelling the fiber on the optical axis defined by the ball lens.

900 µm), a fiber with a diameter of only 125 µm needs to be levered to the same height. This is obtained by a fiber mount as becomes clear from Figure 2.1.10. The electrical connection of the diodes is done with gold tracks, which were prepatterned on the substrate by optical lithography and wet etching.

2.1.4.2 Spectrometer

The LIGA-made microstructures of the heterodyne receiver have a pure mechanical, ie, alignment function. However, they may also have a very distinct optical function as is the case with micro-spectrometers [20], which are illustrated in Figure 2.1.11. Here, white light is coupled into the system by a multimode fiber, which is put in a fiber alignment groove. The light spreads into the free space, forming a hollow wave guide by Fresnel reflections. The light is diffracted at a

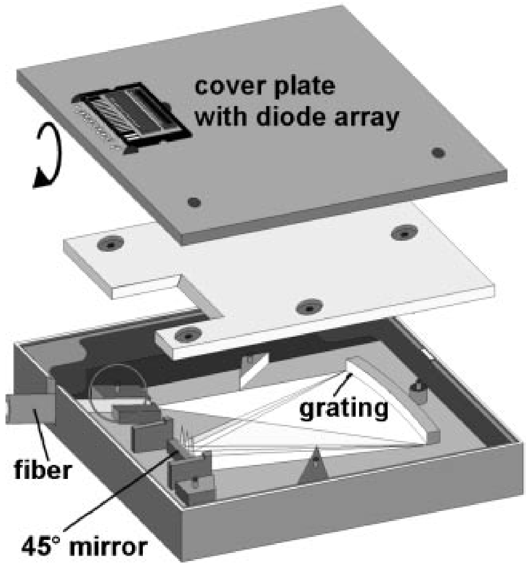


Figure 2.1.11. Schematic of spectrometer.

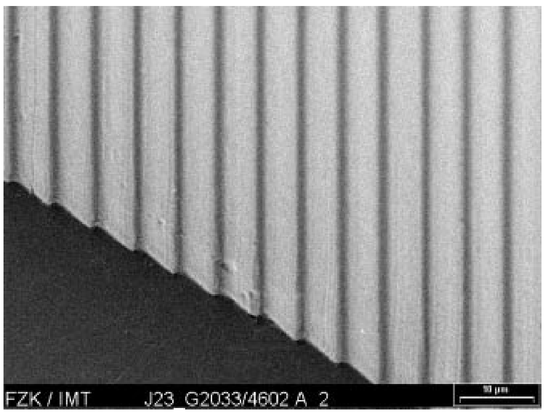


Figure 2.1.12. SEM of grating of molded IR spectrometer.

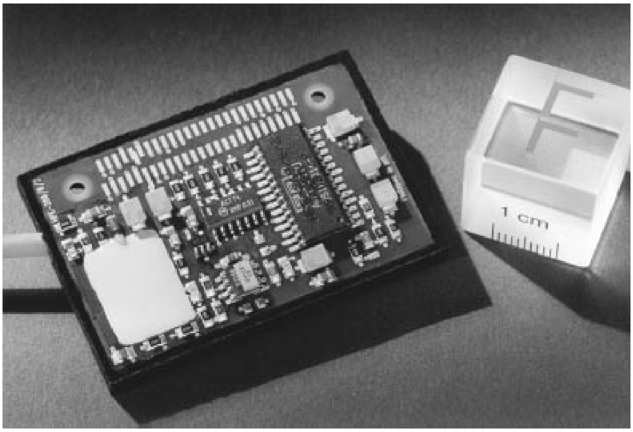


Figure 2.1.13. Full spectrometer system.

reflection grating (Figure 2.1.12), and is coupled out of the system at a 45° mirror next to the fiber. The fiber groove, the grating, and the 45° mirror are fabricated in one step by hot embossing techniques [21] using a molding tool made by LIGA technology. The polymer typically used for hot embossing is PMMA. Hence a gold layer needs to be sputtered on the PMMA structures to make them reflective. A cover plate seals the spectrometer and serves also as the upper surface of the hollow wave guide. An electrooptical chip with a photodiode array and analog electronics is finally put head-over on top of the spectrometer. The full system with the size of a match box is displayed in Figure 2.1.13.

2.1.4.3 Distance Sensor

A similar idea of a hybrid assembly was used for a micro-distance sensor working on the basis of the triangulation principle [22], ie, the position of the spot on the sensor's detector is dependent on the distance of the object to be measured. As with the spectrometer, the distance sensor is divided into two functional units: a passive optical chip again fabricated by LIGA technology including bent mirrors, 45° mirrors, and alignment structures for cylindrical lenses (Figure 2.1.14 a), and an electrooptical chip (Figure 2.1.14 b) with a laser, a photodiode and a position-sensitive detector (PSD). The optical components on the LIGA chip are made from PMMA covered with an evaporated gold layer. Both chips are again mounted head-over to form an opto-electro-mechanical sensor system. For easy assembly, two micro-spheres of glass are used as position aligners of the LIGA and the Si chip (Figure 2.1.14 c). First, the micro-spheres are placed into pyramidal grooves on the Si base, thus centering themselves. Then, the optical chip with two cylindrical holes for the spheres is passively aligned on the Si chip. The two chips before the head-over assembly are shown in Figure 2.1.15. The Si chip is already mounted on a carrier in a TO8 housing.

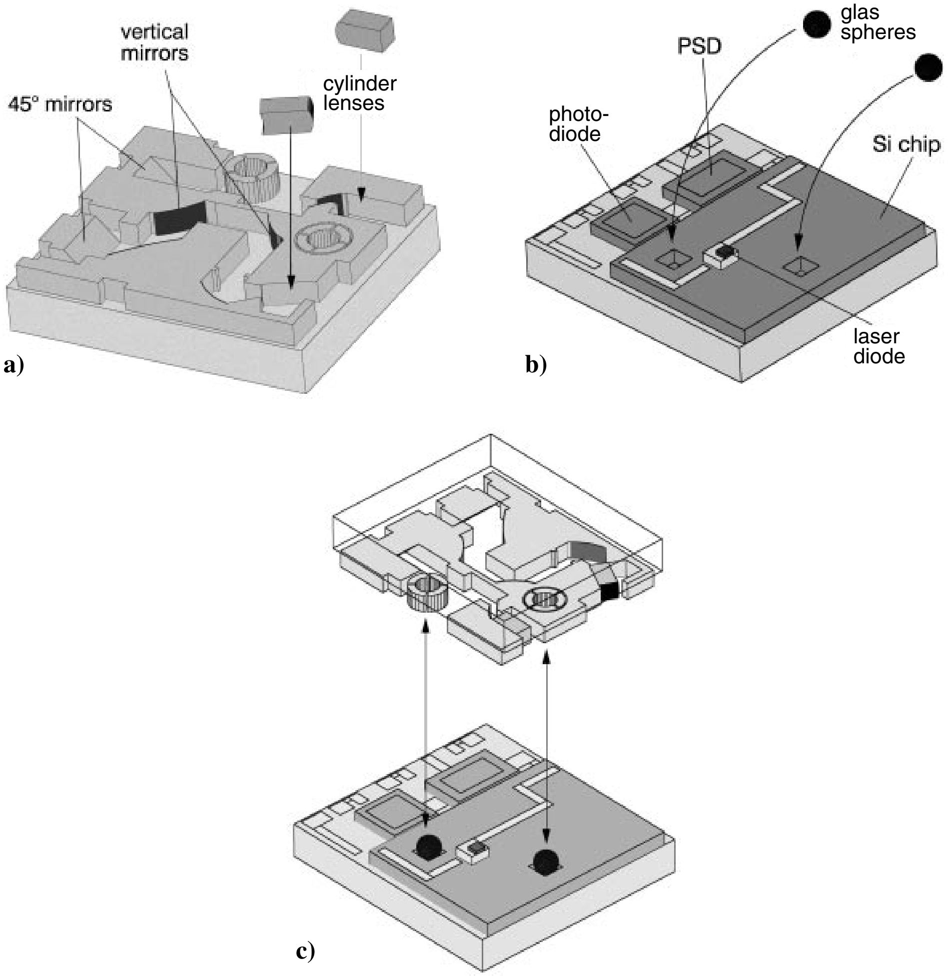


Figure 2.1.14. (**a**) Passive optical chip; (**b**) electrooptical Si chip; (**c**) head-over assembly of opto-electro-mechanical distance sensor system [22] (with permission of Springer-Verlag).

2.1.4.4 Blood Flow Sensor

Not only LIGA structures provide the advantage of optical function in parallel with alignment accuracy. Another good example is a non-invasive blood flow sensor that makes use of the Doppler method [23]. Once again, the device is an assembly of two chips [24], as can be seen in Figure 2.1.16: one Si chip with V-grooves serves as a protection cap for the lower chip, which is an Si substrate with a polyimide waveguide, a laser diode (LD), a photodiode (PD) and electrodes on top of it. The Si substrate was patterned with terraces, Au/Pt/Ti elec-

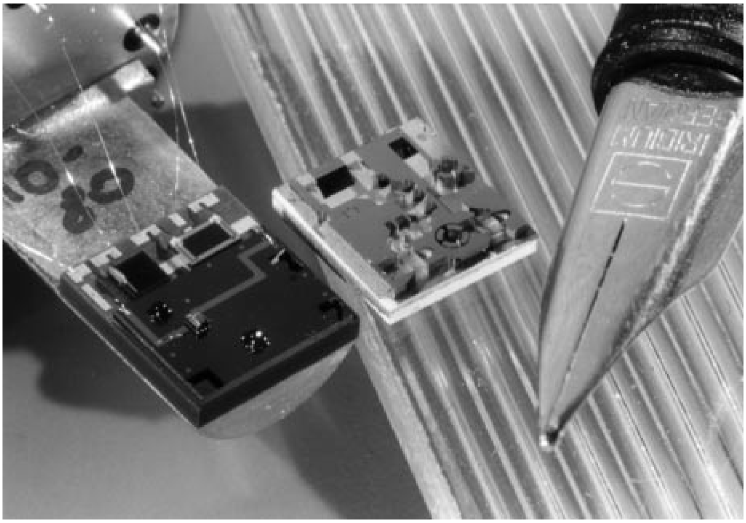


Figure 2.1.15. Photograph of two chips before final assembly [22] (with permission of Springer-Verlag).

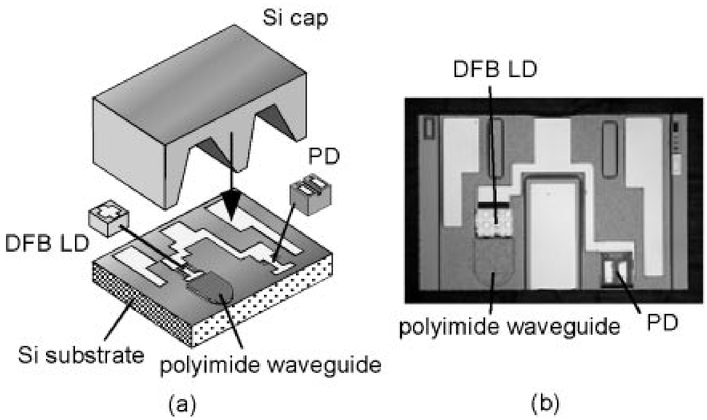


Figure 2.1.16. Schematic set-up of blood flow sensor and photograph of the Si substrate [24] (with permission of IEEE).

trodes, AuSn solder layers, and a three-layer polyimide waveguide. The convex-shaped edge of the waveguide collimates the light from the edge-emitting laser in the horizontal direction, thus allowing operation without the need for an additional lens. Figure 2.1.17 shows a close-up view of the front face of the chip package and the fully assembled sensor system, which is only 20 mm long.

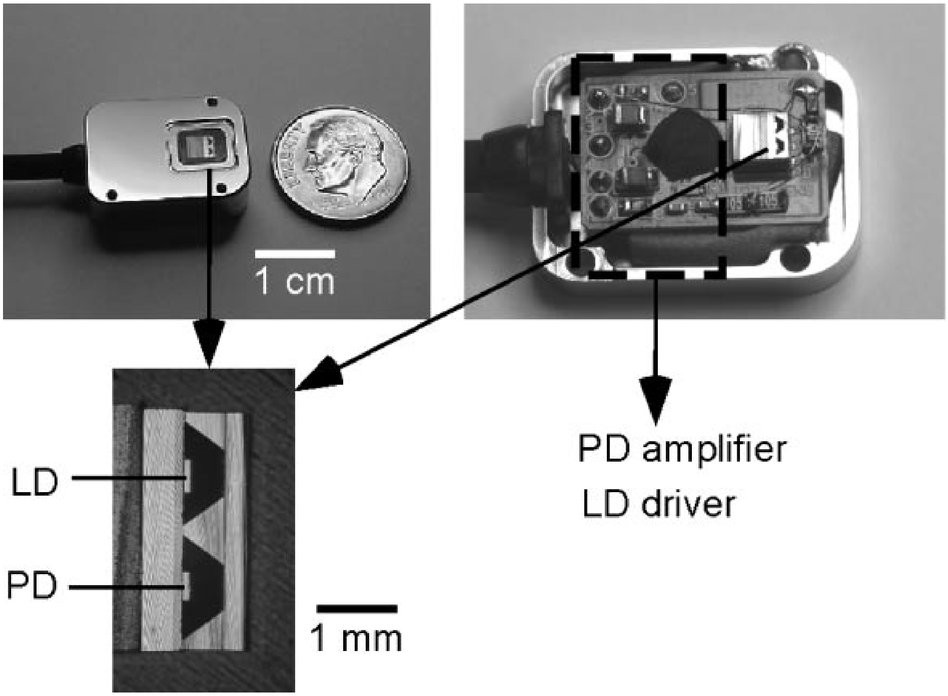


Figure 2.1.17. Close-up of front face of chip package and fully assembled sensor [24] (with permission of IEEE).

2.1.5 Opto-electromechanical Systems 2: Optical Benches Combined with Electrooptical Components and Actuators

In contrast to the preceding section, the idea of a system is now extended by the inclusion of actuators. Again, a modular set-up has the advantage of much easier processes and gives rise to more degrees of freedom for linear movement, rotation, and tilting. Also, the kind of actuation is easier to choose among electrostatics, electromagnetics, piezoelectric or thermal effects, or even hydraulic pressure or capillary forces. The choice of actuation principle is dependent on the required displacement or angle as a function of the force, on boundary conditions such as the available driving current or voltage, the allowed temperature rise, or the environmental conditions in the working area.

This category of opto-electro-mechanical systems is dominated by applications from the telecom field. Although a huge number of publications are concerned with fully integrated systems, there are also some dealing with a modular set-up. No matter whether scanners or switches for fiberoptical networks are discussed, the main focus is put on steerable mirrors. The six systems presented in this section exemplify the variety of kinds of motion and actuation principles. In addition, they represent diverse levels of the modular approach. As already mentioned in the Introduction, we will use the modular microoptical systems of this section to discuss the definition 'modular' once more, now with practical examples.

2.1.5.1 Segmented Deformable Mirror

As in the previous section, a flip-chip-like assembly concept was used for a segmented deformable micromirror array for free-space optical communication as is explained in Figure 2.1.18 [25]. The upper chip contains on its top surface segmented mirrors, which are attached to actuator segments, each of which is suspended from four cantilevers in order to pull them down. The lower chip contains square electrodes to apply electrostatic forces to the actuators and supporting side walls in order to bond the two chips mechanically. All functional elements, ie, the mirrors, actuators, supporting side walls and electrodes, are patterned in polysilicon. For thermal compression bonding, gold bond pads are deposited on top of the side walls and onto the frame of the mirror segments. The spacing between the actuators and electrodes is about 5 μm, which results in displacements of the mirrors of 1 μm at a voltage of 200 V. An SEM photograph of one pixel of the assembled device is shown top-down in Figure 2.1.19. Part of the mirror has been broken off to show the underlying actuator and electrodes.

This concept easily allows one to create large mirror arrays such as 1000×1000 pixels and to put the electrodes directly on integrated circuitry. Thinking on such a big scale, a single mirror is just a component of the whole

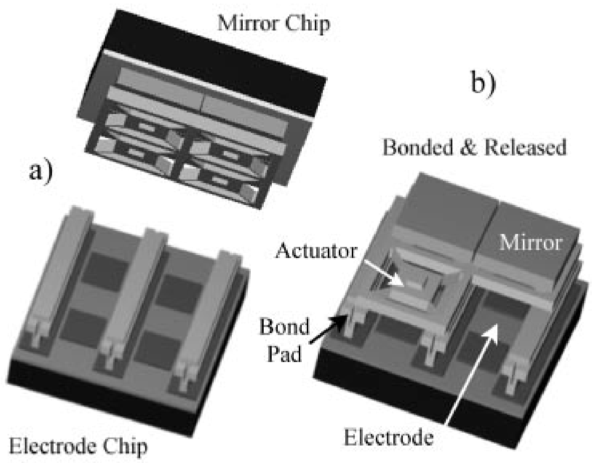


Figure 2.1.18. Schematic 3D drawing of a deformable micro-mirror array before and after bonding. The vertical scale is expanded 10-fold [25] (with permission of IEEE).

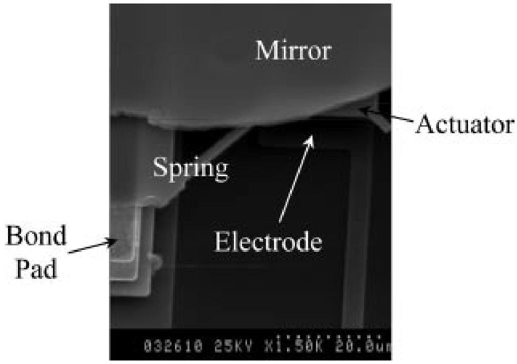


Figure 2.1.19. SEM of a single pixel [25] (with permission of IEEE).

system. However, on a small scale the single mirror can also be considered as a system made of two modules: an opto mechanical (upper chip) and an electrical (lower chip) module.

2.1.5.2 Optical Cross Connect with Linear Motion Actuated by Electrostatics

Again, flip-chip assembly was chosen for an optical fiber cross connect with MEMS switches [26] and integrated waveguides [27]. Figure 2.1.20 shows the MEMS fiber switch made by deep reactive ion etching (DRIE). It consists of two linear electrostatic comb-like micro actuators, which generate a linear movement of the long bar in the center. The mirror (top left corner in Figure 2.1.20), which resembles a needle in this design, is part of the bar and can move into the free space between the grooves for the waveguides. Sixteen of these switches are arranged on the substrate to form a 4×4 switch array as can be seen on the left side of Figure 2.1.21. A second chip provides the integrated waveguides made from SiO_xN_y on SiO_2 also patterned by DRIE. At the position of the mirrors, the waveguides become slimmer in order to bring them as close together as possible and thus reduce optical losses (Figure 2.1.21, right). In addition, the faces of the waveguides can be given an optical shape. The waveguide chip is put head-over on the mechanical chip and fibers are attached to the edges of the package (Figure 2.1.21, center).

In this case, the modular aspect is obvious and easy to find. The two chips have absolutely distinct functions, one for optical waveguiding with integrated imaging, the other providing the electromechanical actuator. Hence the complete system is an assembly of two modules.

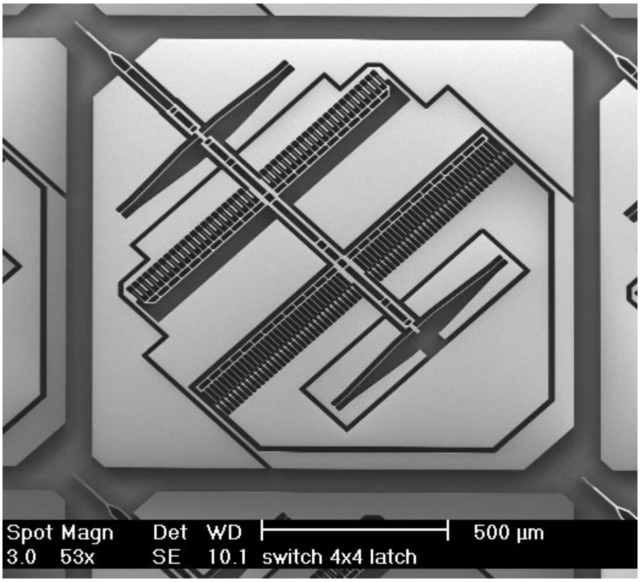


Figure 2.1.20. Flip-chip set-up of 4×4 optical cross connector [27] (with permission of IEEE).

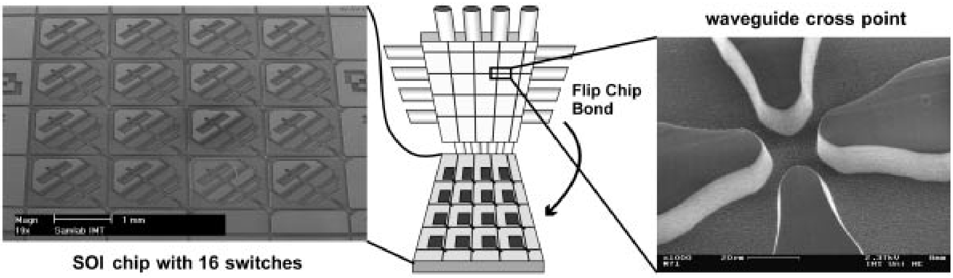


Figure 2.1.21. Close-up view of waveguides at the cross point [27] (with permission of IEEE).

2.1.5.3 Optical Cross Connect with Vertical Motion Generated by Piezo Actuators

A different approach for the realization of a 4×4 optical switch is described in [28]. It is a fully hybrid set-up of mostly commercial components. The principle becomes clear from Figure 2.1.22, which shows a 1×4 channel system. The light from the incoming fiber is collimated by miniature collimation optics. The beam passes four cantilevers with prisms on them. The cantilevers are piezoelectric bimorph actuators, which bend in the vertical direction, thus pulling the 'non-active' prisms below the optical axis. Depending on the position of the only 'ac-

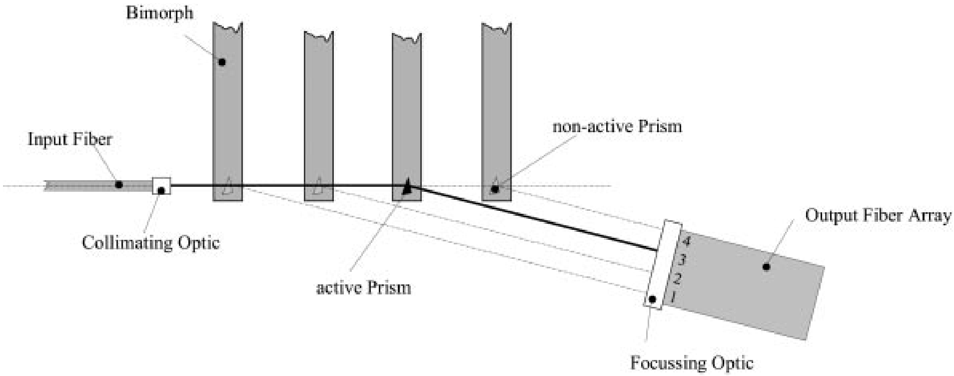


Figure 2.1.22. Schematic drawing of hybrid fiber switch based on piezo actuators [28] (with permission of SPIE).

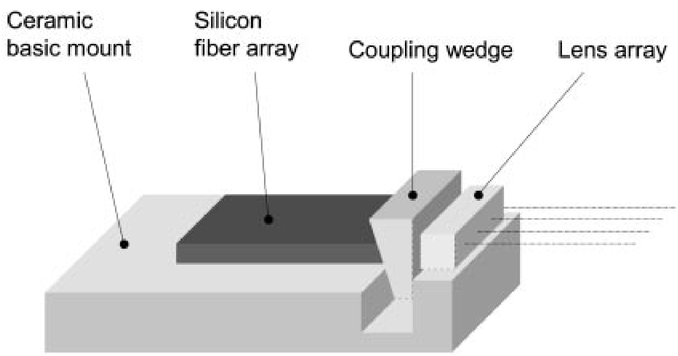


Figure 2.1.23. Schematic drawing of miniaturized focusing optics [28] (with permission of SPIE).

tive' prism, one of the four output fibers is chosen. The light is coupled into the output fibers by means of another miniaturized focusing optics. Multiplying this subsystem by a factor of four, the overall system is obtained. For assembly of the piezo actuators, a ceramic submount providing precise alignment grooves was prepared. The prisms were assembled all in parallel using a vacuum matrix gripper [29] with triangular precision engineered grooves. The miniature focusing optics are shown in Figure 2.1.23. An Si fiber array with an angle polished edge is mounted on a ceramic base. In order to minimize back reflections, a coupling wedge is used to guide the light from the fibers to a micro-lens array. The three components are actively aligned and fixed with UV-curing glue. The full system of a 4×4 switch array after electrical connection of the actuators and fiber insertion is shown in Figure 2.1.24.

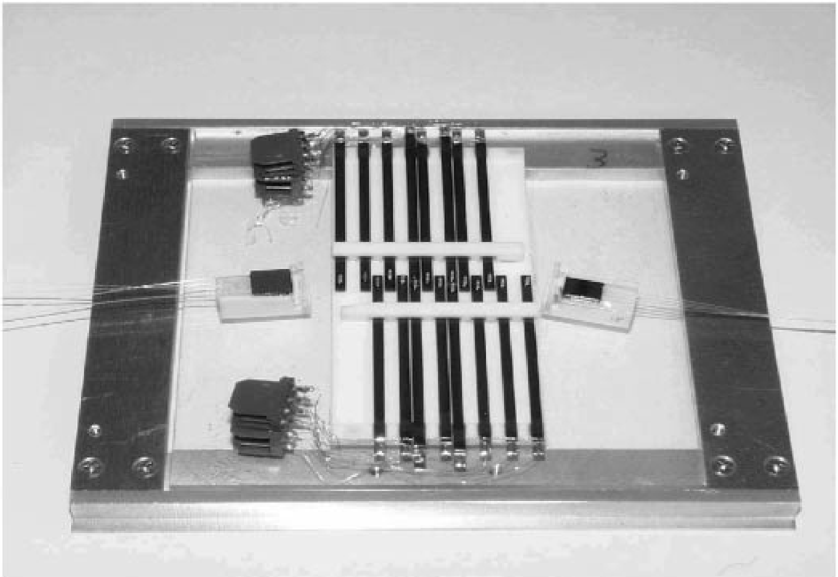


Figure 2.1.24. Fully assembled 4×4 optical switch matrix [28] (with permission of SPIE).

In this modular microoptical system, the hybrid and modular assembly aspects are mixed. The hybrid array of cantilevers with prisms represent the actuator module and the two imaging optics represent the optical modules.

2.1.5.4 Optical Cross Connect with Rotating Mirrors Actuated by Electrostatics

A third assembly strategy for a fiber switch array is to combine a LIGA-fabricated micro optical bench as described above with rotating mirrors, which are arranged in a matrix scheme [30]. Figure 2.1.25 shows the concept for an N×N switch. The light from the fibers is collimated onto the mirror surfaces and refocused into the output fibers by spherical glass lenses. The fibers and lenses are passively aligned with the help of fiber mounts and alignment stops in the optical bench. In order to achieve uniform insertion losses for all channels, the fibers are arranged in a way that all optical pathlengths are the same. The mirrors are attached to the outer side of electrostatic micro-motors, which swivel the mirrors into the beam path. Figure 2.1.26 shows the switching mechanism. Mechanical stops define the correct end position of the mirrors, which were designed as double mirrors in order to ensure always 90° reflection. The optical benches, the static motor parts, and the mirror stops are fabricated simultaneously using LIGA technology. Because of the electromechanical function of the motors, the struc-

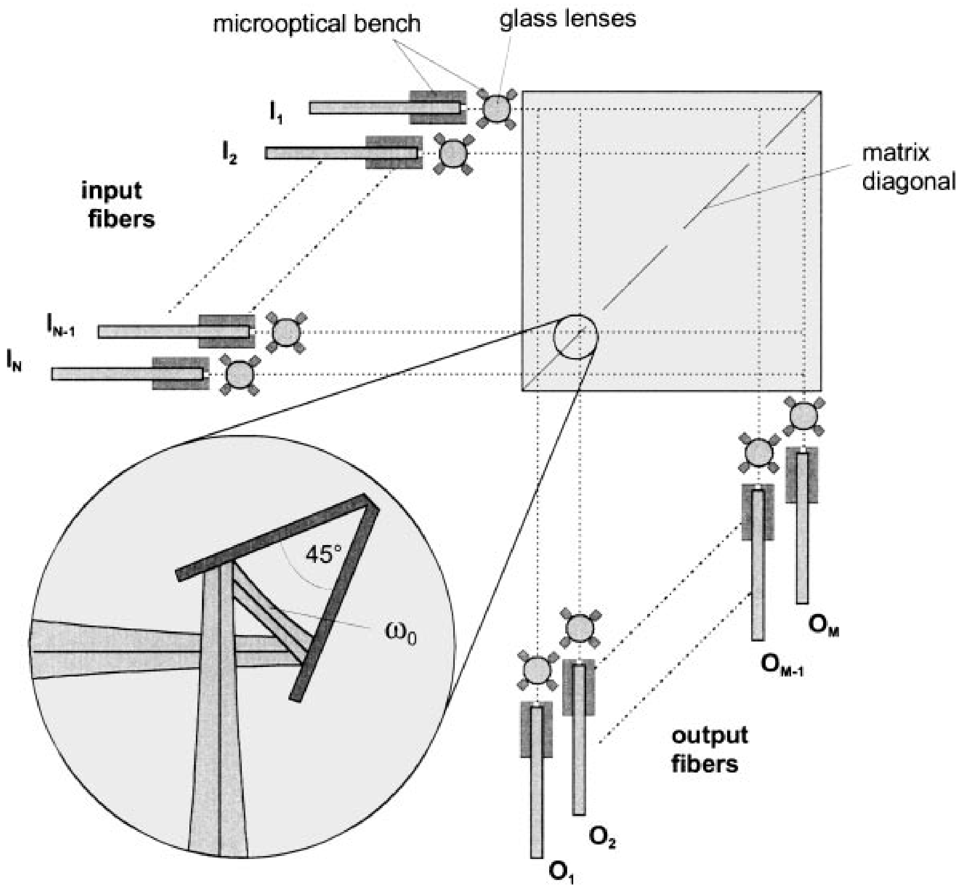


Figure 2.1.25. Schematic drawing of N×N matrix switch using rotating mirrors.

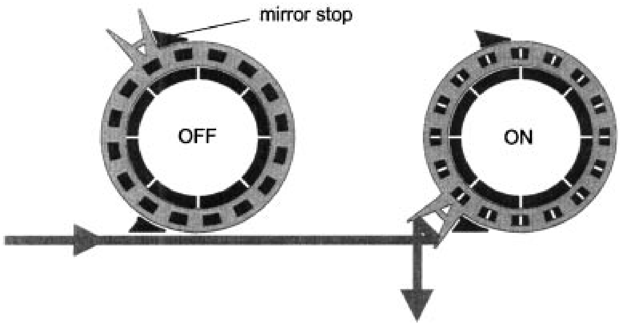


Figure 2.1.26. Switching mechanism of rotating mirrors.

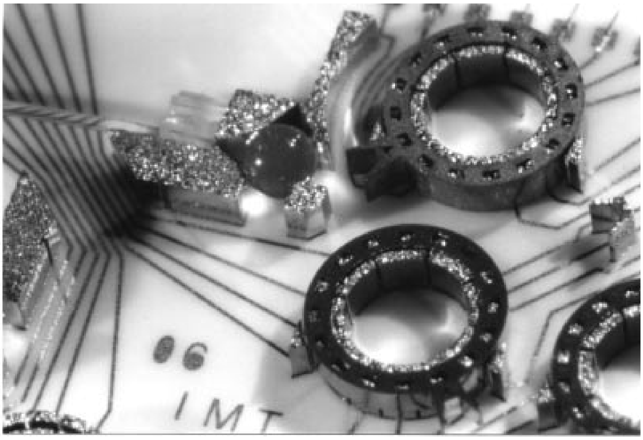


Figure 2.1.27. Close-up view of fully assembled 2×2 switch matrix.

tures are made from electroplated nickel on a sacrificial layer [31]. The rotors with the attached double mirrors are manufactured similarly on a separate substrate and are set manually above the stators. The fiber mounts from PMMA are patterned on a third substrate. Figure 2.1.27 shows a close-up view of a fully assembled 2×2 switch matrix. On the left side, the fiber on the fiber mount and a lens are pushed towards the stop structures of the optical bench. The mirror in front of the lens is in the 'on' position and the mirror below in the 'off' position.

This switch matrix can be considered as a fully hybrid set-up since all components and functions are finally placed on one substrate although they have been fabricated on three substrates in total. It is a question of preference to define the optical part with fibers and lenses as the optical module and the rotating mirror as the mechanical module.

2.1.5.5 Oscillating Modulator for Infrared Light Actuated by Electromagnetics

To complete this section about opto-electro-mechanical systems including actuators, two examples from the sensor field are given. The first is a modulator, ie, a chopper, for infrared light for suppression of noise in infrared spectrometers [32]. The working principle becomes clear from the demonstrator shown in Figure 2.1.28. Alignment structures for input and output fibers are patterned on a ceramic substrate in parallel with a movable shutter (looking like a small hammer in Figure 2.1.28) and an electromagnetic actuator, which becomes obvious from the coil in the upper part of the picture. The structures are fabricated using LIGA technology and electroplating of Permalloy, which is a soft magnetic alloy of 80% nickel and 20% iron. A current flowing through the coil generates a magnetic field, which is guided through the metallic yoke. Owing to the decrease in

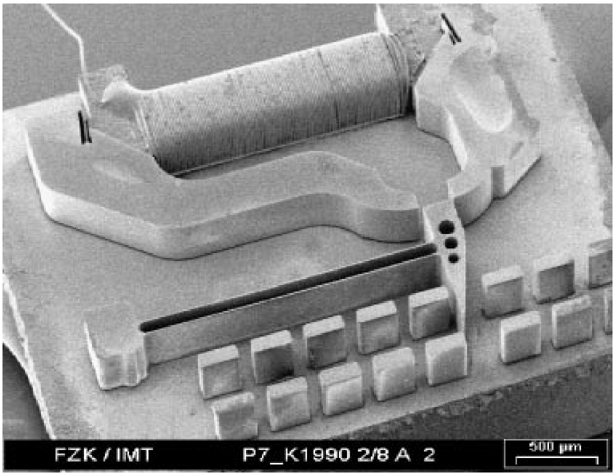


Figure 2.1.28. Demonstrator for electromagnetic microchopper.

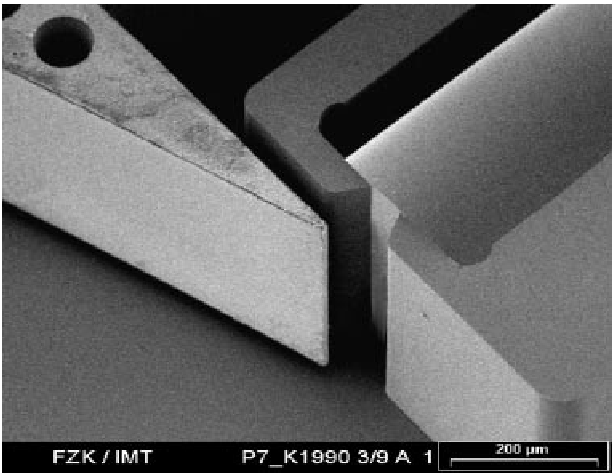


Figure 2.1.29. Close-up of shutter in front of fiber.

the resistance of the magnetic circuit, the shutter is pulled backwards between the pole shoes of the circuit, thus enhancing the metallic cross section for the magnetic field. A sinusoidal current generates a periodic field and an oscillation of the shutter. The yoke for the coil is manufactured on a separate substrate and released. The coil is wound manually so far and then assembled on the substrate using alignment and clamping structures. For integration of the chopper in a spectrometer (discussed above in Section 2.1.4), the fiber alignment structures are skipped. The chopper is put head-over in the light-input part of the spectrometer. This is facilitated by four stops on the edges of the yoke and the fixing block of the shutter, which were patterned simultaneously for this purpose. Figure 2.1.29 shows a close-up view of the very precise position of the shutter tip directly in front of the input fiber of a spectrometer in its alignment groove.

The final system of the spectrometer including the chopper is a full modular assembly of an optical and an electromechanical module. The chopper itself is a pure hybrid device.

2.1.5.6 Laser Scanner for Barcode Reading Actuated by Electromagnetics

The second sensor example is a laser scanner for barcode reading [33] with a similar actuation principle as the chopper. Figure 2.1.30 shows a schematic drawing of the scanner. Again, a magnetic circuit with an assembled coil is fabricated from Permalloy by means of LIGA. A perpendicular mirror is attached on a freely suspended metal anchor, which is part of the magnetic circuit. The air gap in the circuit and therefore, the magnetic resistance are minimized when the an-

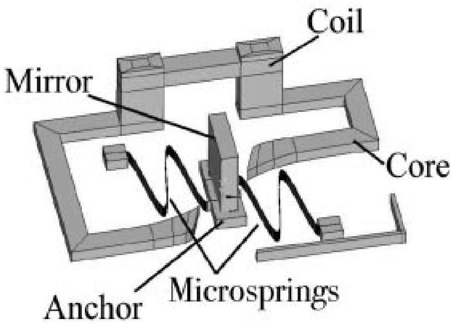


Figure 2.1.30. Schematic drawing of a laser scanner for barcode reading.

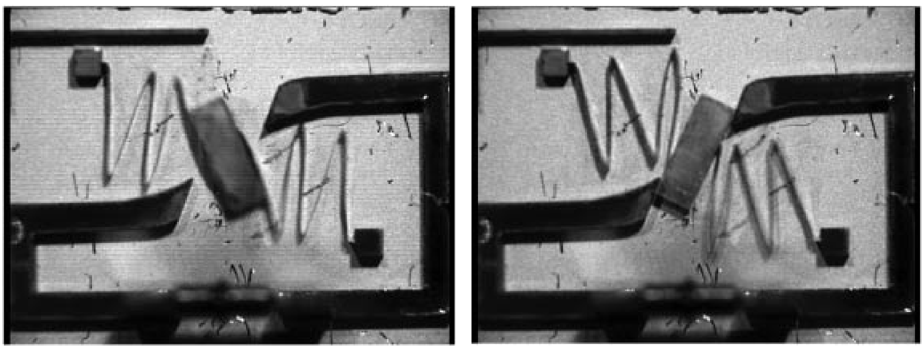


Figure 2.1.31. Stroboscopic photographs of a scanner at a deflection angle of 20°.

chor is deflected towards the ends of the pole shoes. As above, a periodic current will generate an oscillation of the mirror with twice the current's frequency. The mirror is made from a 100 µm thick Si wafer, which is coated with a reflective Au layer and cut to pieces of $1.5 \times 1.6\ mm^2$ by a wafer saw. It is placed in an alignment groove, which was patterned in the anchor and is fixed by adhesive bonding. At a current of 20 mA, the scanner reaches a scan angle of 12° in a nonresonant mode. Figure 2.1.31 demonstrates the motion with two stroboscopic photographs.

Like the chopper discussed before, the scanner is a hybrid device. In this case, however, it is a module in a 'macroscopic' optical system, which so far is not made by means of micro-technology.

2.1.6 A Final Word About Assembly Technology

No matter what categories of opto-electro-mechanical systems were discussed above, they all had one common task: assembly! Many components could be assembled passively using alignment aids such as stops or grooves, which were directly patterned into the basic structures or substrates. If not, alignment had to be done actively, which means that the performance of a device is optimized while it is operated and the components are still under positioning control. For the fabrication of demonstrators or prototypes, both assembly strategies are done more or less manually. However, for industrial fabrication, automatic assembly procedures are desired. Several research groups are concerned with that target and are developing grippers, bonders, dispensers for adhesives, and so on.

Some specific aspects for the assembly of microoptical devices are listed in [34]. The components have various but typical shapes such as spheres (ball lenses), cylinders (mirrors, GRIN lenses, fibers), plates (mirrors, lens arrays) or prisms (beam splitters). They are small, of low weight and have smooth surfaces, which enhances adhesion. They are sensitive to electrostatic fields or mechanical stress, the material typically is brittle so careful handling with the necessity of sensing small gripping forces is required. Finally, the most important goal is not to damage the optical surfaces of the components that have to be picked and placed. These handling conditions are also valid for all items concerned with storage in magazines and transportation. Some examples given in [34] are a magazine for cylinder lenses (Figure 2.1.32), a gripper for active alignment of prisms (Figure 2.1.33) and a fiber gripper and manipulator (Figure 2.1.34). The magazine allows safe storage of the cylinder lenses in a reproducible position. It provides a defined interface to the other assembly equipment with sufficient space between the lenses to pick them up. The fiber manipulator consists of two grippers, the first for stress relief and the second to pick the fiber at its uncoated tip and for fine positioning, eg, when the fiber is threaded through a hole as indicated in Figure 2.1.34.

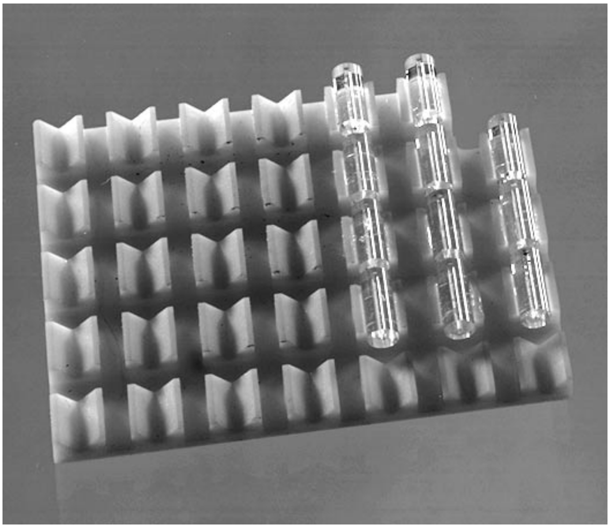


Figure 2.1.32. Magazine for the storage of cylinder lenses [34] (with permission of SPIE).

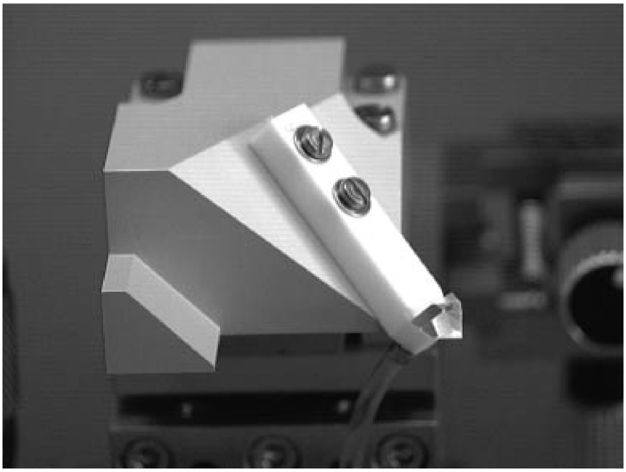


Figure 2.1.33. Gripper and alignment system for prisms [34] (with permission of SPIE).

A complete system for automatic assembly of a microoptical duplexer [35] for which ball lenses, monomode fibers, and wavelength filters have to be assembled into an optical bench and a housing is described in [36]. The authors have developed magazines and grippers for all components. All grippers work by vacuum suction except the one for the fibers. For proper material flow during assembly, a complete tray on a *xy*-stage was developed which carries all magazines as sketched in Figure 2.1.35. The tray is pushed towards three reference pins to ensure a precise

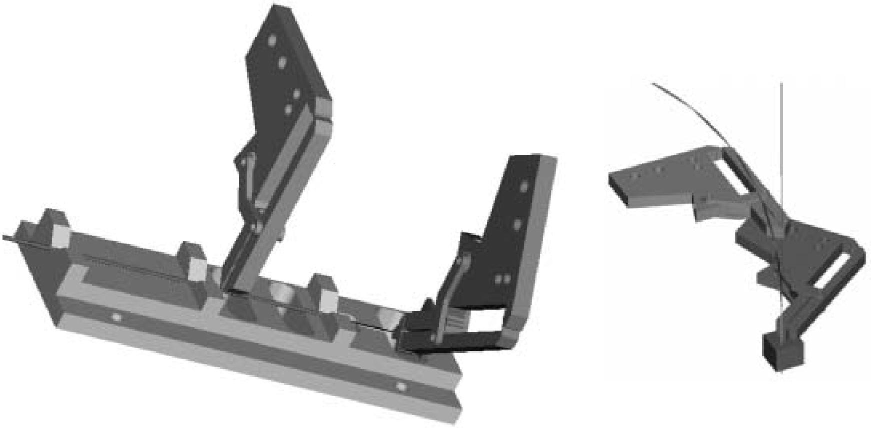


Figure 2.1.34. Gripper and manipulator for fibers [34] (with permission of SPIE).

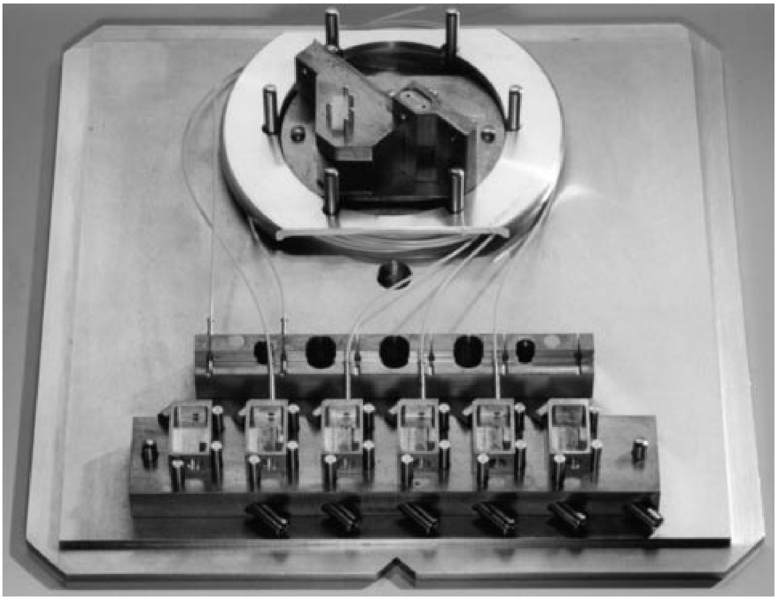


Figure 2.1.35. Work tray containing magazines for material flow during automatic assembly.

position in the overall automatic assembly set-up. The magazines allow the storage of the pieceparts of six duplexer systems, which means that always one tray is in the assembly machine, and a second can be filled off-line with pieceparts in parallel. The diverse grippers and a dispenser for adhesive are mounted on a tool turret, which allows a fast change of tools while occupying only limited space because of its compact construction, as can be seen in Figure 2.1.36.

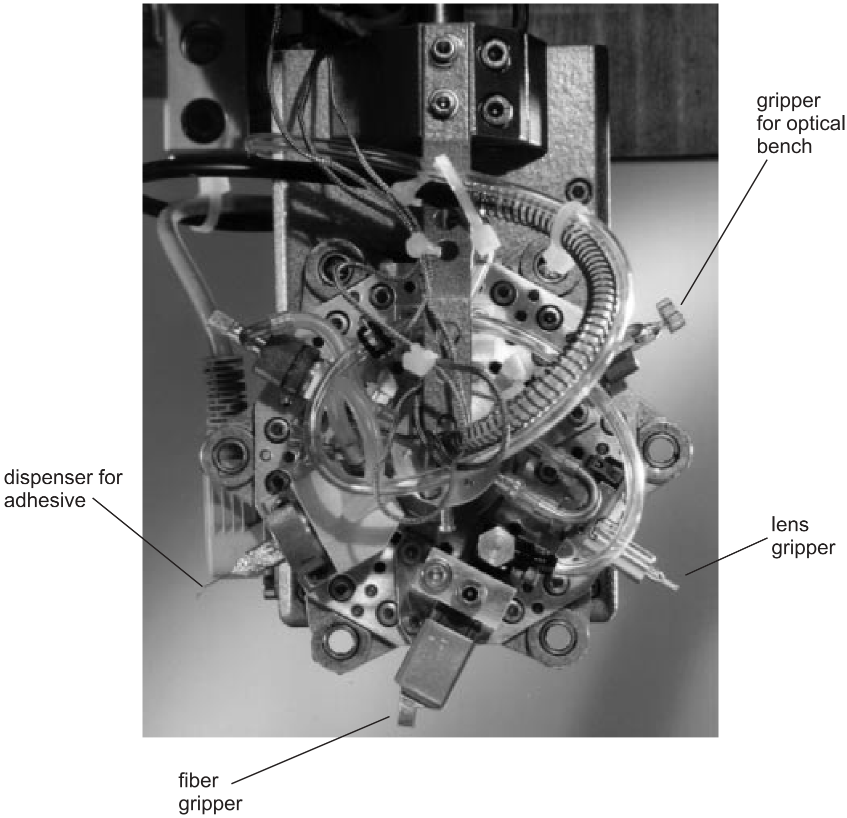


Figure 2.1.36. Tool turret carrying grippers and a dispenser.

One very essential task for alignment and assembly is free sight to the devices no matter whether microscopes are used for manual assembly or cameras for automatic processes. More complex positioning strategies are reported in [38] in the case of flip-chip assembly when the devices are mounted head-over and are hidden one behind the other. As indicated in Figure 2.1.37, a laser chip is to be put on a fiber submount. Both chips carry reference structures as alignment aids. One positioning strategy is explained in Figure 2.1.38. The gripper for the laser chip is also equipped with reference marks. When the chip is attached to the gripper, the relative position of the chip to the gripper can be calculated from the image, which is detected by a camera below the chip. In the next step, the fiber submount is placed under a camera looking from above in order to calculate the relative position of the submount with respect to the gripper. Finally, the flip-chip assembly is done automatically using the calculated coordinates by an *xy*-stage. Another strategy makes use of a prism as an image splitter as shown in Figure 2.1.39. In this case, the camera is placed beside the assembly, a prism is inserted in the free space between the two chips, and the reference marks of both chips are displayed in parallel. This set-up allows a closed-loop control of the alignment.

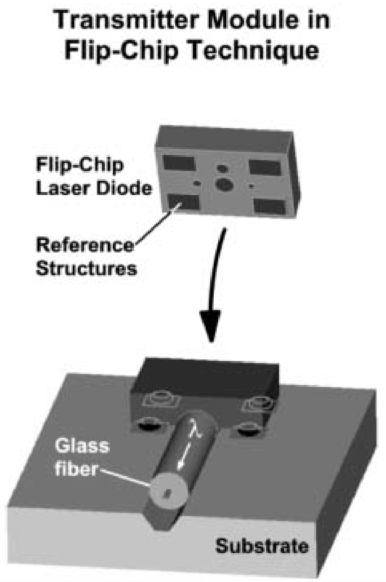


Figure 2.1.37. Flip-chip assembly of a laser chip on a fiber submount [37] (with permission of SPIE).

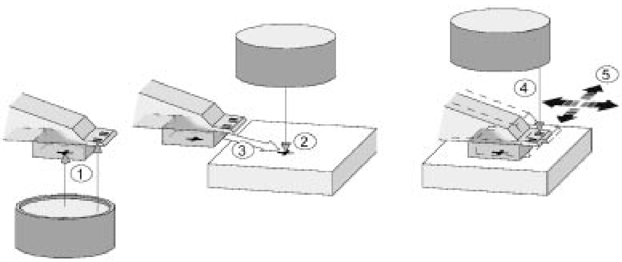


Figure 2.1.38. Alignment strategy for flip-chip assembly using markers on the chip-gripper [37] (with permission of SPIE).

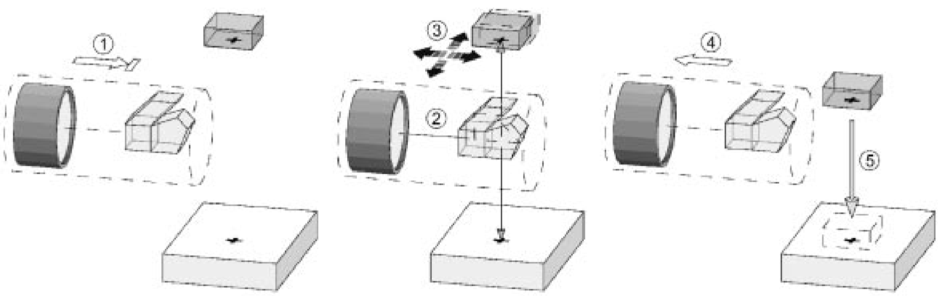


Figure 2.1.39. Alignment strategy for flip-chip assembly using prisms as image splitter [37] (with permission of SPIE).

2.1.7 Conclusions

We have presented a wide variety of modular microoptical systems for telecommunication and sensors. In doing so, we have distinguished between pure opto mechanical devices and opto-electro-mechanical systems. Some of them represent the modular aspect just very basically such as the fiber connectors (Section 2.1.3) or the segmented mirror (Section 2.1.5.1). Other systems follow almost completely the modular method of design and manufacturing such as the distance sensor (Section 2.1.4.3) or the fiber switch array (Section 2.1.5.2).

It is obvious from the wide range of concepts that we have described that the modular approach is convenient and helpful in order to produce more and more complex systems for always higher demands and broader applications. It allows one to fabricate the separate modules with adapted processes, which are not too difficult and time consuming and therefore not too expensive.

On the other hand, one has to ensure that these advantages are not overcome by the costs and problems due to the consequently necessary assembly. Research and development are performed for hybrid solutions, eg, magazines and assembly tools for single components such as lenses or fibers are investigated. However, for a real modular approach to manufacturing and assembly, new strategies need to be found. Microfabricated components should not be first released from their substrate, then be collected in a magazine which perhaps does not provide sufficient position accuracy for a gripper to pick it up again without any need for imaging. In contrast, the method of assembly already needs to be considered in an 'assembly friendly' design of the diverse components and modules and in their fabrication process.

The most important task, however, is the clear and unequivocal definition of interfaces. This is relevant for all aspects of hybrid and modular design and manufacturing, not only for micro-optics but for all kind of systems. It includes interfaces for on-going fabrication such as substrate size and chip size, compatible materials, how an intermediate product is supplied to the next fabrication step, all assembly features including dicing, bonding, and packaging, and – finally and often forgotten – measurement methods with well-defined critical values.

The developers of modular micro-systems have to work hand in hand with the developers of the assembly tools and also of the fabrication equipment. The more they stick to the interfaces and standards, which mostly still need to be defined, the more they can use their developments for several modules or even other purposes. This will make the modular approach economically feasible at least for smaller and medium numbers of pieces such as are often required especially in the sensor field.

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List of Abbreviations

Abbreviation	Explanation
DRIE	deep reactive ion etching
LD	laser diode
MEMS	micro-electro-mechanical system
MOEMS	micro-opto-electro-mechanical system
PD	photodiode
PMMA	poly(methyl methacrylate)
PSD	position-sensitive detector
SEM	scanning electron microscope
LIGA	LIthography, Galvanik (electroplating), Abformung (molding)