Optical coupling structure made by imprinting between single-mode polymer waveguide and embedded VCSEL

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ABSTRACT

Polymer-based integrated optics is attractive for inter-chip optical interconnection applications, for instance, for coupling photonic devices to fibers in high density packaging. In such a hybrid integration scheme, a key challenge is to achieve efficient optical coupling between the photonic chips and waveguides. With the single-mode polymer waveguides, the alignment tolerances become especially critical as compared to the typical accuracies of the patterning processes. We study novel techniques for such coupling requirements. In this paper, we present a waveguide-embedded micro-mirror structure, which can be aligned with high precision, even active alignment method is possible. The structure enables 90 degree bend coupling between a single-mode waveguide and a vertical-emitting/detecting chip, such as, a VCSEL or photodiode, which is embedded under the waveguide layer. Both the mirror structure and low-loss polymer waveguides are fabricated in a process based mainly on the direct-pattern UV nanoimprinting technology and on the use of UV-curable polymeric materials. Fabrication results of the coupling structure with waveguides are presented, and the critical alignment tolerances and manufacturability issues are discussed.

Keywords: optical interconnect, single-mode waveguide, optical coupling, UV nano-imprinting, polymer photonics, integrated optics

1. INTRODUCTION

1.1 Rationale

As the signal line rates have increased above 20 Gbps and are further increasing, the use of optical interconnects instead of copper is becoming more and more attractive in terms of power efficiency and interconnection density in the high throughput and performance computing and communication systems. This is driving towards the vision of optically interconnected system where the optical transceivers are integrated on/next to the processor ICs and the optical fibers are coming to the board/package with their signals smoothly coupled to the processors and PICs. Later on, the optics will also be interconnecting between the processors on the board and the package.

For the board and package level interconnects, integrated optics and waveguides based on optical polymer materials are an attractive media solution, since the polymer waveguides generally promise suitability on various kind of substrates (i.e. on the circuit boards and package/chip carriers), scalability on large area manufacturing, and cost efficiency. Polymer waveguides also allow good mode matching to both fibers and photonic devices for high coupling efficiency. Thus the polymer waveguides are also suitable and attractive coupling between densely integrated laser diode (esp. VCSEL) and photodiode arrays and the optical fiber arrays, because the smaller array pitches of the VCSELs and PDs can be extended to the fiber array pitch via the waveguides.

Traditionally, the development of the board-level optical interconnects has mostly focused on the use of multimode waveguides, which are often coupled to VCSEL-based (vertical-cavity surface emitting laser) transmitters. However, the future scenario of a generic interconnect media suggests to use single-mode waveguides. This is because the intra-system interconnection length-bandwidth products are extending beyond the reach of the multi-mode fibers (especially in large data-centers) and because the smooth scalability to longer reach fiber links requires single-mode fibers. Furthermore, because the PICs, such as the emerging silicon photonics technology, are inherently based on single-mode waveguides, it is more straightforward to also implement all out-of-chip/package interconnects using the single-mode technology too.

The aforementioned scenario calls for polymer waveguide technology with low optical losses and with integrated coupling structures for efficient optical coupling between the waveguides and the active devices and optical fibers. Recently, the authors have been studying and developing such a single-mode polymer waveguide based photonic circuits technology within the joint European FIREFLY research project.[1]

1.2 The polymer photonic technology platform

Nanoimprint patterning is one way to fabricate single-mode polymer waveguides. Basically in imprinting the surface profile of the stamp is replicated onto liquid polymer. Figure 1 describes the imprint-based process for making inverted-rib type polymer waveguides. Wafer-scale UV-NIL has been proven to be a suitable method in fabrication of integrated optics.[2]–[4] The main advantage of wafer-scale UV-imprinting is the ability to pattern relatively large areas with a single step while maintaining the resolution of about tens of nanometres. This makes it attractive for low-cost volume production. Also 2.5-dimensional patterning is possible, such as, slanted or curved side walls. This enables combined processing of optical waveguides and coupling structures, such as, micro-mirrors. In addition to the wafers, the process is applicable to other kind of substrates, such as, sheet-like circuit boards. UV NIL is often a room temperature process, so there is very little shrinkage and distortion of the pattern, which also enables to achieve good overlay accuracy.

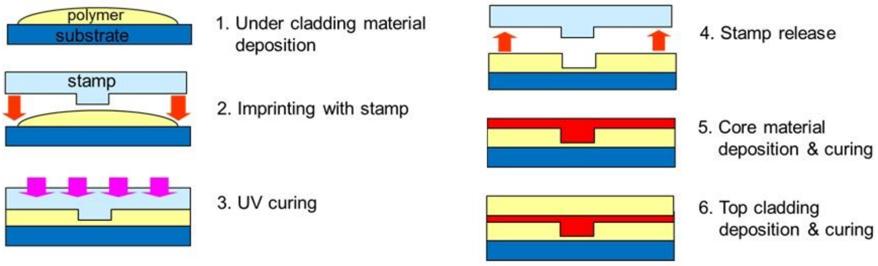

Figure 1. The process to fabricate inverted rib polymer waveguides by UV imprinting.[6]

VTT has developed direct-pattern UV nanoimprinting processes for fabrication of polymeric integrated optics, including also multilayer waveguide structures, and demonstrating that low optical losses (thanks to smooth surfaces), good wafer-scale yield, and high overlay alignment accuracy are possible.[5]–[8] Both the mastering and replication process steps were developed. In the FIREFLY project, the single-mode polymer waveguides were optimised for operation at around 1300...1600 nm wavelengths and mode field diameter of 6–7 µm. The waveguides fabricated of ORMOCER materials (by Micro Resist Technology GmbH) had cross-sectional core dimensions of circa 5 µm.[8] Examples of such waveguides made of OrmoClad and OrmoCore are shown in Figure 2.

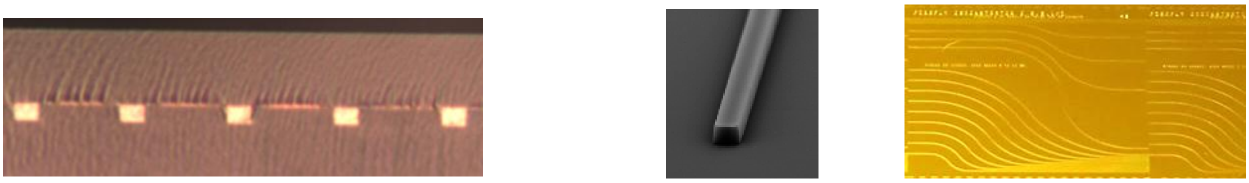

Figure 2. Imprint-based Ormocer waveguides: left) Cross-section of five parallel inverted-rib waveguides, showing very thin (0.5 µm) slab layer; middle) SEM of ridge waveguide with end facet; right) Waveguides of varying bend radii on a wafer.

A major obstacle for the applicability of the waveguide-based interconnects is the lack of volume-producible low-loss coupling technology from the vertically emitting devices to the planar waveguides, although various technologies have been studied by many groups. With the aforementioned single-mode polymer waveguides, the alignment tolerances become especially critical as compared to the typical accuracies of the patterning processes. In this paper, we focus on the implementation of an integrated 90° bent coupling mirror, which can be fabricated by imprinting into the polymer waveguide layer. In particular we demonstrate a concept where the coupling mirror is used with VCSELs embedded under the waveguide layer[9],[10] and we present a fabrication method which enables very high precision alignment of the mirror to the VCSEL and waveguide.

2. MIRROR COUPLING CONCEPT

The micro-mirror technology was investigated and developed for the integration scheme presented in Figure 3. This scheme was adopted in the FIREFLY project.[1] Si chip/wafer is used as the integration substrate. Thinned VCSEL chips are mounted into cavities on the substrate and embedded under the single-mode polymer waveguide stack. Micro-mirror is used to enable 90° bent VCSEL-to-waveguide coupling. Further, a single-mode fiber can be attached to the fiber assembly enabling waveguide-to-fiber coupling. The concept is also applicable to waveguide-to-photodiode coupling as well as to multi-channel devices (i.e. VCSEL/PD arrays and fiber ribbons) for parallel optic links.

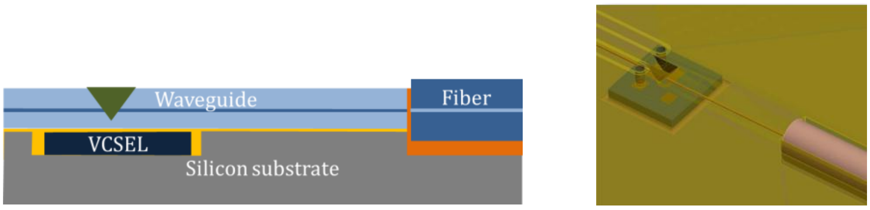

Figure 3. Basic schematics of the overall integration concept for VCSEL-to-waveguide and waveguide-to-fiber coupling. Left) Cross-section, Right) 3D illustration.

In more detail, the envisioned imprinting based mirror structure, which would be compatible with the embedded VCSEL technology and suitable for mass-manufacturing, is sketched in Figure 4. This enables embedding the coupling mirror inside the waveguide material stack. Further, by metal coating (for instance, Au layer) the mirror surface for high reflectivity, the structure can be embedded inside the polymer stack, thus protecting the mirror during the potential subsequent assembly steps and in the end-user environment.

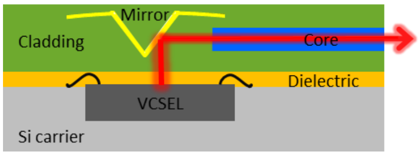

Figure 4. Proposed embedded metal micro-mirror for coupling from embedded VCSEL to polymer waveguide.

2.1 Modeling

The mirror coupling structure was studied by optical modeling of losses with varying dimensions and manufacturing tolerances, such as, layer thickness, misalignments, and tilts. Gaussian beam propagation modeling was used. Assuming that the waveguide mode-field diameter is 6 µm and the VCSEL beam waist is 3 µm, the divergence of the beam starts to limit the maximum achievable coupling efficiency when the VCSEL-to-waveguide separation increases, as seen in Figure 5. Loss of 1 dB is possible with separation of 20 µm or less. It is around the minimum applicable separation with this waveguide design, because approximately 15 µm-thick under-cladding layer is required to avoid leakage of the mode (i.e. loss). 2 dB loss is achieved at the separation of ca 35 µm, which is already relatively easy to implement. At these separation distances, the coupling efficiency appeared relatively sensitive to both misalignments and tilt angles.

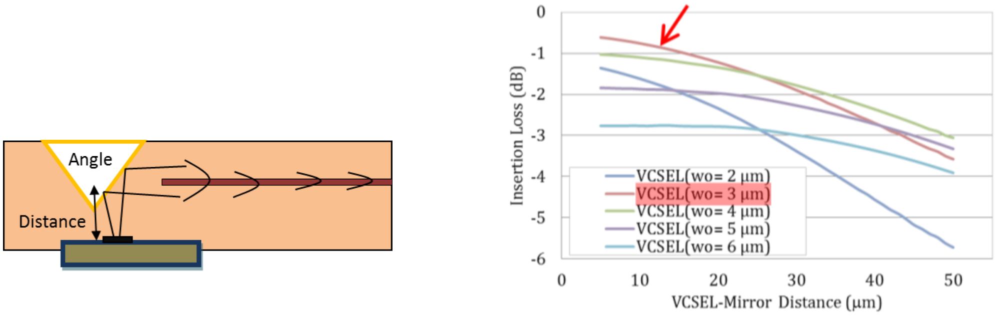

Figure 5. Optical modeling of the VCSEL-to-waveguide coupling: left) The structure. right) Coupling loss as a function of VCSEL-to-mirror separation for varying VCSEL beam waists. Beam waist of 3 µm pointed with arrow. (When waveguide mode-field diameter is 6 µm and mirror-to-waveguide separation is fixed to 5 µm.)

On the other hand, when using the similar structure for coupling from a waveguide to a photodiode, the alignment tolerance requirements are significantly relaxed, because the typical diameter of a PD, even when suitable for 25 Gbps data rates, is much larger than the waveguide mode field.

2.2 Wafer-level fabrication

Obviously, in cost-efficient volume manufacturing the coupling mirrors should to be patterned in a wafer-scale process, that is, by one step patterning and simultaneous alignment of all mirrors on the wafer. This requires an imprinting wafer stamp which includes several mirror molds, as depicted in Figure 6. More precisely, the wafer-scale stamp should include all mirrors needed to be imprinted over the wafer, and those mirror structures should be positioned at submicron accuracy with respect to each other over the wafer. Otherwise all mirrors would not become properly aligned for good coupling efficiency. And obviously the mold structures have to have very smooth 45° degree mirror facets. This limits the choice of potential stamp/mold fabrication technologies. Potentially applicable mastering methods include laser patterning or grey-scale lithography patterning of the master stamp as well as the use of micro-mirror inserts which are fabricated separately and the mounted on the wafer stamp.

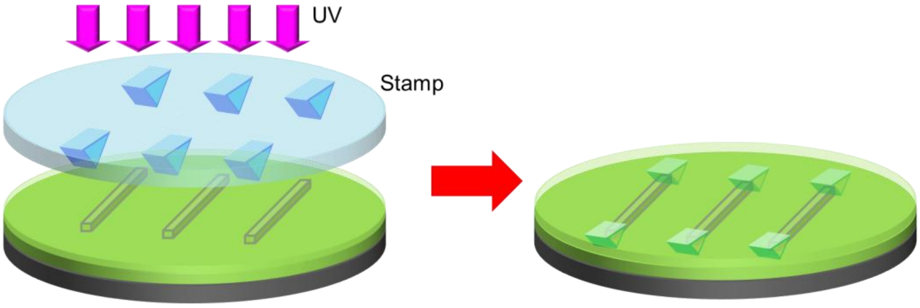

Figure 6. Schematic illustration of the wafer-scale imprint patterning process of the micro-mirrors on the waveguide layer.

Furthermore, wafer scale imprinting of the mirrors is possible only if all VCSELs are very precisely mounted with respect to each other over the wafer and also the waveguide layer is precisely aligned to all VCSELs. In practice, with the presented waveguide technology, the acceptable alignment tolerances for the mirror, VCSEL and waveguide are in the order of micron or less in all dimensions and also the angular misalignments should be very small. It has been shown that 1 micron scale overlay tolerances are achievable in the waveguide patterning[8], and thanks to mask lithography based mastering technology[5], the waveguides become very precisely aligned with respect to each other, thus enabling wafer-scale alignment.

2.3 Mirror imprinting using active alignment

Since the alignment and fabrication of a wafer-scale stamp for patterning all mirrors in one step is challenging, we also developed an alternative mirror imprinting method, where each mirror is imprinted on the wafer separately and stepwise. That is, the imprinting is made using a single mirror stamp/mold and the material is UV-cured locally. This method, illustrated in the center of Figure 7 (Phase 3), enables to align the mirrors separately to each VCSEL chip and waveguide pair. If monolithic multi-channel VCSEL array chips are used, the method enables mirror alignment separately to each VCSEL array chip and the corresponding waveguide array. A significant advantage of the method is that it also enables to use active optical alignment method, i.e. finding the most optimal position based on the monitoring of the coupling efficiency from the other end of the waveguide with a fiber and a photodetector. However, the active alignment method is suitable for the fine adjustment only, whereas the initial rather accurate alignment has to be made by passive alignment methods, which are typically based on machine vision and registration marks.

Figure 7 presents a potential complete fabrication process envisioned for the fabrication of embedded coupling mirrors on embedded VCSELs by the use of local imprinting with a prism and possibly also active alignment. First (Phase 1), the VCSELs are embedded and electrically contacted, and the whole waveguide stack is fabricated on top of the embedded VCSELs (using processes described earlier). In Phase 2, grooves are made on the waveguide stack at the position of the mirror above the VCSELs. Laser ablation is an applicable method for making the grooves. In Phase 3, the mirrors are made one by one into the grooves by filling the groove with top-cladding polymer into which the mirror is imprinted in two steps: aligned and locally UV cured. In this stepwise imprinting method, the material of imprinted mirror may be deposited locally on top of the corresponding VCSEL only. Finally in Phase 4, a metal (e.g. gold) layer is deposited on the mirrors for high reflectivity and patterning the metal e.g. by resist mask process, and in Phase 5, the whole structure is covered with another protective polymer layer, for instance, of the top-cladding material. In some applications, the structure may also be used without the protective layer or even without the metal layer applying total internal reflection.

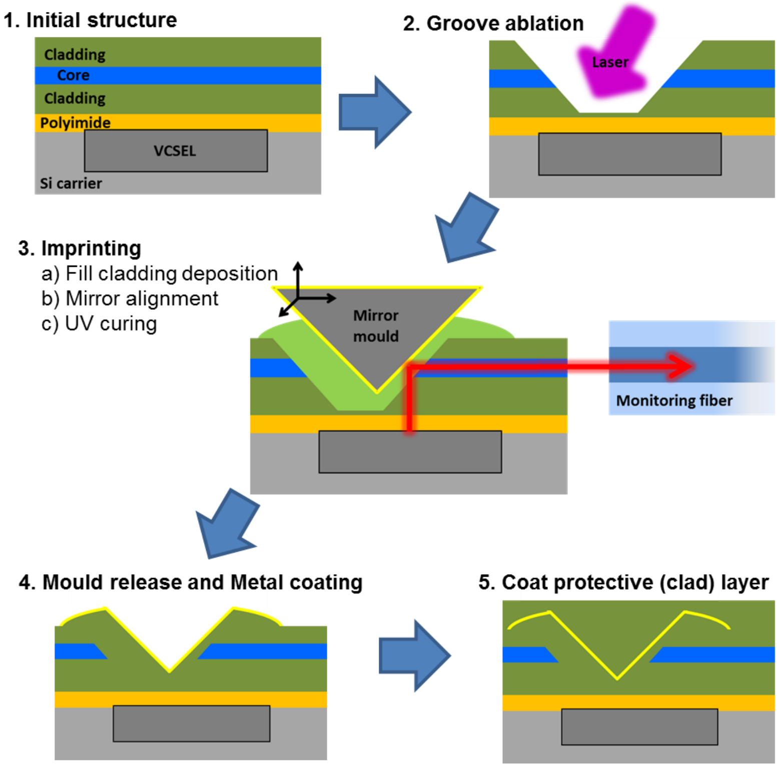

Figure 7. Process flow for mirror fabrication by local imprinting and active alignment method.

An advantage of the laser ablation technology here is that a tilted side wall of the groove can be fabricated (as depicted in Figure 7). This enables very short separation between the mirror surface and the waveguide core, thus reducing the coupling loss as compared to the case of vertical wall.

Since the groove is filled with the cladding material, the refractive index contrast in the interfaces is very small. An advantage is that no significant scattering occurs even if the surfaces of the groove are not smooth.

Similar manufacturing and alignment process is applicable for embedded photodiodes too, except that the optical power would be coupled from the fiber towards the PD (through the waveguide) and the active alignment would be based on the monitoring of the PD photocurrent.

3. IMPLEMENTATION

Feasibility of the proposed mirror fabrication technology was investigated by experiments. Some of the first results are presented here.

3.1 Embedding of VCSELs and waveguide fabrication

First step was to fabricate sample chips with embedded VCSELs and waveguides above the VCSELs. The structure is depicted in Figure 8 left. VCSELs were embedded in pockets on the wafer substrate and covered with a polyimide planarization dielectric layer. Vias were laser ablated on the polyimide and filled with copper for electrical connections. Finally, the waveguide stack was fabricated on top of the polyimide layer so that the waveguide cores became accurately aligned with respect to the VCSEL emitting areas.

In the mirror fabrication experiments, samples having waveguides fabricated by two alternative methods were used: Part of the samples had waveguides made of EpoCore/Clad material (by Micro Resist Technology GmbH) and patterned by the laser direct imaging method[10]. The other samples had waveguides made of OrmoCore/Clad materials and patterned by imprinting method described in Figure 1. Figure 8 (right) shows an example of an embedded VCSEL under imprinted Ormocer waveguide with good alignment between the VCSEL active area and the waveguide core.

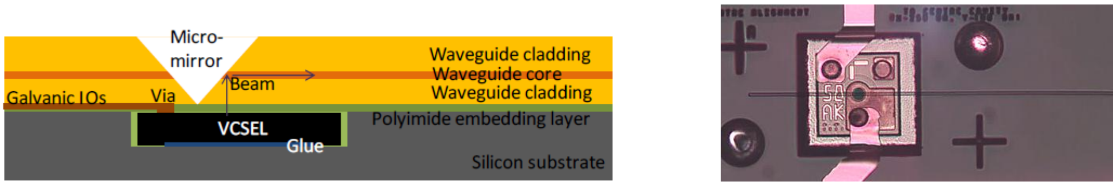

Figure 8. Left) Structure of the samples used in the mirror coupler experiments.[10] VCSEL is embedded under the waveguide stack. Also the location of the mirror element illustrated. Right) Micrograph of a fabricated sample showing embedded VCSEL under imprint-patterned waveguide core.

3.2 Mirror by insert-based master

The process of wafer-scale imprint patterning of micro-mirrors (as illustrated in Figure 6) was evaluated. To make the master stamp, micro-mirror mold inserts were first fabricated by polishing the edge of a thinned silicon sheet in such a way that 45° tilted mirror facet was obtained with smooth surface. Then the actual mold inserts were got by dicing the sheet into small chips. Then the inserts were adhesive bonded on a master stamp wafer by high-precision flip-chip bonder, as shown in Phase 1 in Figure 9 left and using the layout shown in the middle. To finalize the master stamp, an anti-sticking monolayer coating was applied to enable proper stamp release after imprinting. For manufacturing on Si wafers, an UV-transparent wafer stamp is then made by two successive imprinting (negative) replications of the master stamp on glass wafers. However, in the first experiments, the fabrication was made on glass substrates, thus the master stamp was directly applicable. The mirror patterns were imprinted in Ormocer material patterning as described in Phase 2 in Figure 9 left. After an Au coating was applied on the mirrors (Phase 3), clear vertical reflections were seen at 1550 nm and only 1 dB mirror loss was observed.

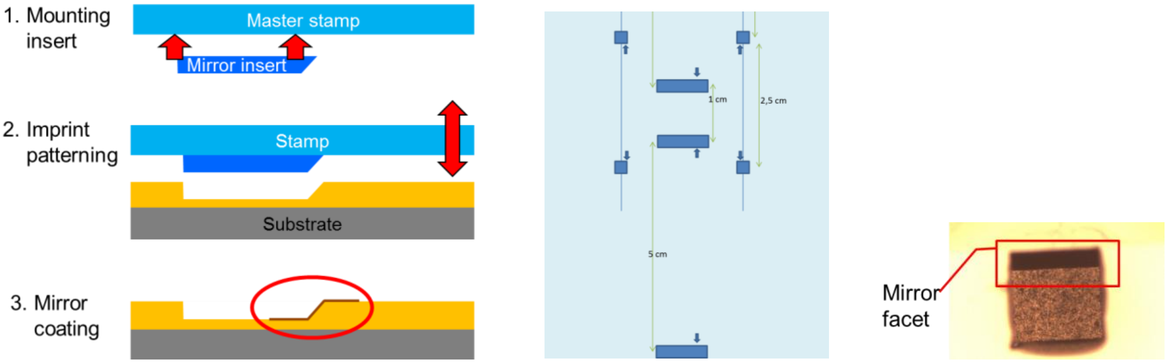

Figure 9. Coupling mirror imprinting by insert-based mastering: Left) The main process steps. Middle) Layout in the experiment. Right) Micrograph of an imprinted mirror.

3.3 Local imprinting and active alignment

The local mirror imprinting concept (presented in Chapter 2.3) and the active precision alignment method in it were evaluated and demonstrated.

A glass micro-prism was selected to be used as the mold insert in the first experiments, because micro-prisms of suitable size and shape were readily available and because as optical components they have high quality facets with very low roughness. For the high reflectivity needed during the active alignment, the micro-prisms were first Au-coated. The Au and anti-sticking coated prism mold was attached to the automated active alignment and assembly station. For easier attachment with station’s micro-grippers, each prism was first attached to a larger support bar. Then also a sample Si chip including embedded VCSELs with electrical contacts and polymer waveguides above the VCSELs is placed on the substrate carrier of the alignment station under the mold, as seen in Figure 10 left.

Next the imprinting with the micro-prism mold was tested. A droplet of OrmoClad material was deposited on the sample and the mold was used to imprint into the droplet which was UV cured before detaching the mold. An image of an imprinted mirror structure shown in Figure 10 (right) demonstrates that the targeted mirror shape and smooth surface were achieved.

Figure 10. Coupling mirror imprinting: Left) Sample chip with waveguides and embedded VCSELs under the mirror imprinting mold in the precision alignment station. Also the monitoring fiber used in the active alignment is seen. Right) SEM image of a mirror imprinted in Ormocer by the micro-prism mold. (Note: the residual particles are from the dicing, which was used to make the cross-section sample for SEM.)

The mirror alignment and imprinting process was successfully demonstrated. Figure 11 (left) shows the top view of the embedded VCSEL sample and a mirror mold in the alignment and imprinting station. This enabled the camera based initial alignment of the mold. In the final precision alignment, the VCSEL power reflected from the mirror mold is monitored. This reflection is illustrated in Figure 11 right. During the active alignment of the mirror mold, the VCSEL output power coupled to the waveguide was monitored with the fiber which was first aligned to the waveguide (as seen Figure 10 left).

Figure 11. Alignment in mirror imprinting: Left) Part of a sample chip with embedded VCSELs and waveguides seen from above with an alignment camera. Right) During the precision alignment the mirror mold is moved to find the optimal position as e.g. illustrated here with the green arrows. Here the red spot visible on the IR detection card is used to illustrate that when properly aligned on the top of the VCSEL the mold reflects the VCSEL beam 90° towards the card.

4. CONCLUSIONS

An embedded coupling structure was developed. It enables 90 degree bend optical coupling between VCSEL/PD and single-mode polymer waveguide. The developed manufacturing process of both the waveguides and the coupling structure are based on imprint patterning of UV-curable polymers. Mirror fabrication processes based on the use of mirror inserts as molds as well as on the local imprinting and active alignment methods were demonstrated. Also future prospect on wafer-scale process for volume manufacturing was presented. The technology is attractive for optical interconnection applications, for instance, for optical interposers and out-off package interconnects, such as, coupling between VCSEL/PD arrays and fiber ribbons in high density photonics integration.

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