



Modular and Reconfigurable 3D Micro-Optical Benches : Concept, Validation, and Characterization

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Abstract—In this paper, we present an approach to design MOEMS based on Reconfigurable Free Space Micro-Optical Benches (RFS-MOB). The proposed concept enables to design modular and reconfigurable MOEMS by using a generic structure of silicon holders and non defined position in the substrate. Various micro-optical elements, e.g. microlenses or micromirrors, can be integrated within holders. Their assembly is achieved with an active microgripper, after high precision alignment within guiding rails of silicon substrate. Flexible parts are used to maintain a final position. The concept is validated by successful assembly of holders. A characterization method of assembled holders is proposed and provides an accuracy better than $\pm 0.04^\circ$ for an angle measurement.

I. INTRODUCTION

Over the last past decade, the demand for miniature devices has continuously increased then MOEMS (Micro-Opto-Electro-Mechanical-Systems) fabrication has become an important challenge. Hybrid integration of heterogenous micro-optical components on a same substrate, as opposed to monolithic approach, constitutes a promising solution. It consists in the mounting of different micro-optical components coming from various sectors of manufacturing on a substrate. Recent results validate the fabrication of MOEMS based on micro-optical benches [1], [2], [3], [4], as microspectrometers [5], [6], miniature microscope [7] or LIDAR (Light Detection And Ranging) [8]. We observe for these applications that the position of each optical element on the substrate is predefined in the layout of photolithography mask or definite joining is performed. The attachment is achieved by different way: silicon springs in the slot or/and UV (UltraViolet) curing. There are some results about characterization of assembled objects like [8] for millimetric objects, [9] for tilt measurement and [7] for one assembled micro-objet with SEM (Scanning Electron Microscope).

Multiscale assembly, especially serial precise micro-assembly demonstrate very encouraging results [10], [11], [12]. It lead to the development of micro-assembly stations which integrate flexibility, modularity, precision and repeatability. Due to the microfabrication tolerances and the numerous possible applications of MOEMS, the development of new Free Space Micro-Optical Benches (FS-MOB) which are generic with non predefined position is proposed. It enables to design different applications with rapid prototyping and to characterize micro-

optical components. An active gripping ensures reversible locking systems and a fine positioning of micro-objects like a beam splitter assembly for microspectrometer in [13]. For the precise control of position and the alignment of optical path, the 3D micro-assembly station is essential. Teleoperated mode is performed for the concept validation but the final objective is the automation of the micro-assembly process which is the set of tasks (grasping, insertion, guiding, releasing). In this aim, the study of guiding task is performed [14] with specific microscale strategy [15].

The accuracy and the repeatability of the RFS-MOB concept combined to micro-assembly station have not yet been characterized. They are not only linked with robot accuracy but also micro-assembly strategy, microfabrication tolerances, controller parameters, surface forces, ...

In this paper, we briefly recall the concept of RFS-MOB, his fabrication and validation, afterwards we propose his characterization. In the following, the concept of RFS-MOB is described in Section I. Section II presents his fabrication and his validation. Section III discusses about the characterization of assembled micro-optical element. Finally, Section IV provides some conclusions and perspectives.

II. CONCEPT OF RFS-MOB

The concept of RFS-MOB is based on robotic micro-assembly of various micro-optical elements as micromirror (1), beamsplitter (2), and holder with ball lens (3), integrated with removable silicon parts (holders), on a bulk-micromachined universal silicon substrate (baseplate) [16]. The baseplate constitutes rigid and stress-free mechanical support, characterized by excellent surface quality and equipped with a set of two-directional micro-mechanical rails (FIGURE 1). The holder permits the optical element to be hybrid or monolithically integrated within its structure and then to be assembled on the rail in arbitrarily chosen position. Using a developed 3D micro-assembly station, the holder can be actively aligned with nanometer precision along the rails and finally fixed by releasing of the mechanical locking system, like snap connector. Further adjusting of holder position or replacement of a damaged holder is possible, ensuring reconfigurability of optical system. Thus, variation of the optical parameters, e.g. focal length of microlens etc., can by precisely compensated.

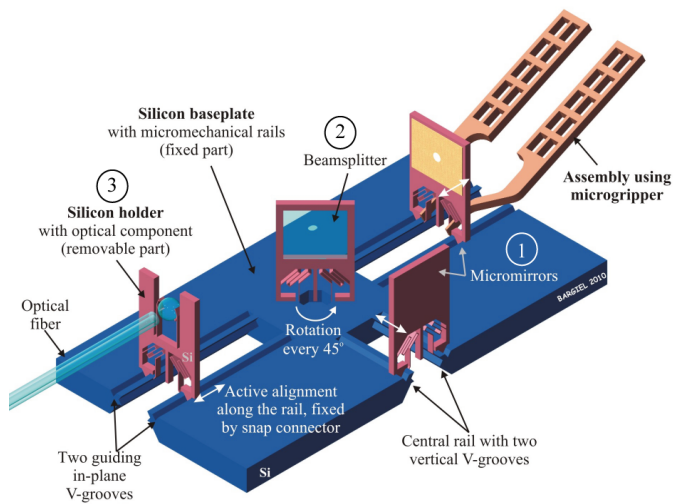


Fig. 1. Concept of RFS-MOB based on the substrate and holders assembled by active microgripper.

The fine control of holder position on the rail is of great importance to ensure the usefulness of the RFS-MOB. In order to achieve this goal, a set of compatible V-grooves is produced both in baseplate and holders by anisotropic etching of silicon (FIGURE 2 -(1)). Two standard in-plane V-grooves and two “vertical” ones are formed in substrate. In-plane V-grooves create guiding rails as well defined surfaces of reference for other microparts of RFS-MOB. For instance, the holder is in contact with these rails through two protruding grooves, formed by DRIE (Deep Reaction Ion Etching). Whereas “vertical” V-grooves enable mechanical fastening of the holder onto the substrate. FIGURE 2-(2) shows detailed view of the snap connector, integrated within the structure of each holder. It is composed of two $10\ \mu\text{m}$ thick silicon multi-folded springs, which are adjusted to the shape of central rail of the substrate.

III. FABRICATION AND VALIDATION

A. Fabrication of RFS-MOB elements

The substrate was fabricated on n-type, $\langle 100 \rangle$ oriented wafer. The crucial parts which are the rails, were formed in $300\ \mu\text{m}$ thick membrane, back-side wet etched in KOH (potassium hydroxide) solution using thermal SiO_2 (silicon dioxide) mask. The original shape of central rail with two vertical V-grooves was obtained by DRIE etching for the width and the deep of the trench and subsequently wet KOH etching of vertical sidewalls. Each vertical sidewall was converted into two $\langle 111 \rangle$ oriented sidewalls, inclined to each other at the angle of 110° . After stripping of the SiO_2 layer, the wafer was divided into chips by diamond saw dicing. FIGURE 3 shows an example of fabricated structure.

The holders were fabricated in a $50\ \mu\text{m}$ thick device layer of n-type, $\langle 100 \rangle$ oriented SOI wafer with $1.0\ \mu\text{m}$ thick buried oxide layer (BOX) and $400\ \mu\text{m}$ thick substrate layer. The structures were etched into the device layer by DRIE, using thermal SiO_2 mask. In order to release the structures, cavities were back-side etched through the substrate layer by KOH

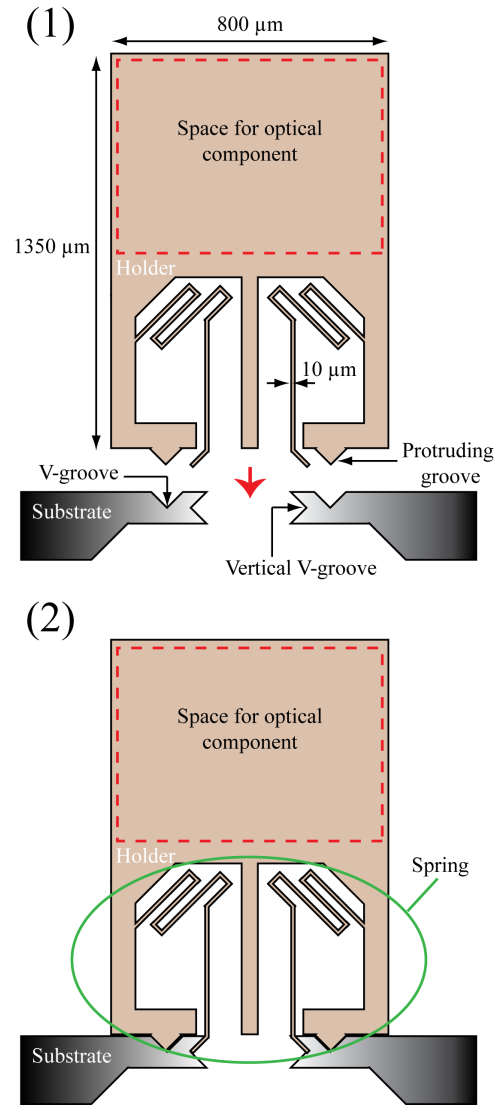


Fig. 2. Principle of reconfigurable micro-optical benches: (1) before assembly, (2) holder locked on the substrate.

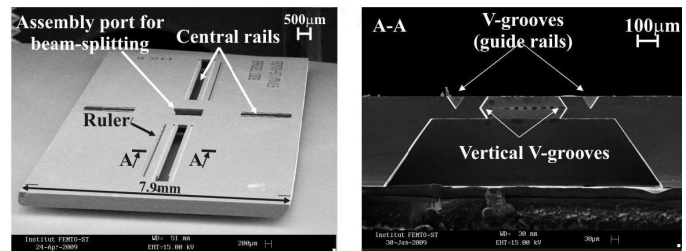


Fig. 3. The results of substrate fabrication.

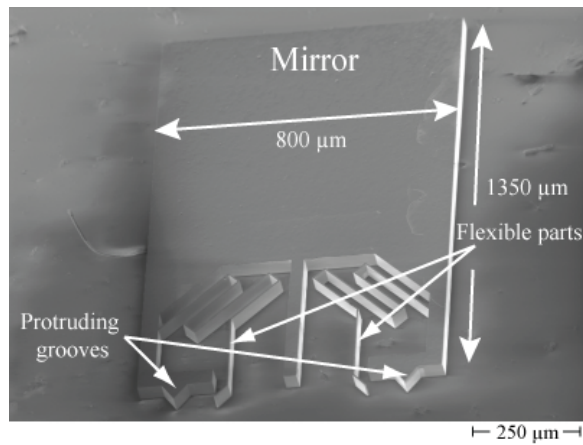


Fig. 4. The result of holder fabrication.

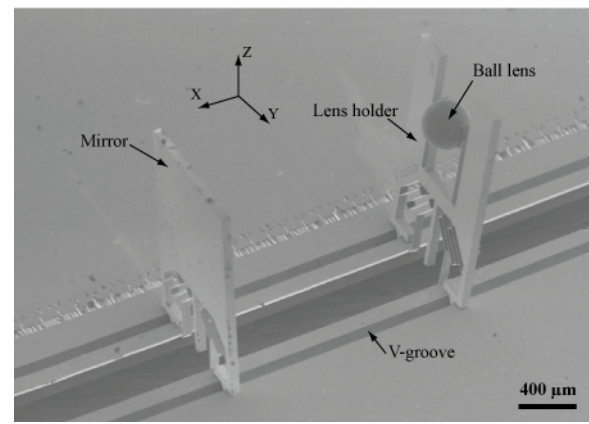


Fig. 6. The results of micro-assembly with mirror and lens holder.

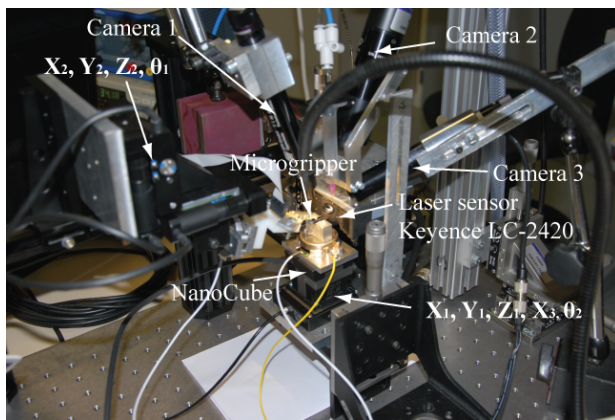


Fig. 5. The 3D micro-assembly station for RFS-MOB assembly.

solution. A chuck (AMMT, Germany) was employed to protect already formed silicon structures on the top side. Finally, the exposed area of BOX as well as SiO_2 mask were etched in BHF (hydrofluoric acid) solution to release the holders. Different types of holders, equipped with micro-optical components (e.g. micromirrors) or prepared to be hybrid integrated with it (e.g. ball microlens), have been fabricated. The result of mirror fabrication is shown in FIGURE 4.

B. Validation of RFS-MOB concept

In order to perform serial assembly, the workcell comprises a robotic structure, vision system, and a microgripper. The proposed 3D microrobotic assembly system is a structure with nine DOF motorized stages arranged into two robotic manipulators. The micro-assembly station is presented in FIGURE 5.

Fabricated substrates and holders are used to validate the concept of RFS-MOB. The developed micro-assembly station is used with piezoelectric microgripper. Some micro-assembly are performed and results are presented in FIGURE 6. They validate the RFS-MOB concept based on serial robotic micro-assembly, flexible parts for fastening and passive alignment.

IV. CHARACTERIZATION

Micro-assembly of RFS-MOB requires an accurate positioning of holders on the substrate. This is challenging since many factors may influence the final result [17], e.g. the quality of the motion generated by micropositioning stages, the microgripper control, microfabrication tolerances, surface forces, stability of the grasp, stiffness of the spring, etc. There are very few studies have been carried out to characterize the positioning accuracy of assembled microparts [7], [8], [9]. Due to the sizes of holders, it is necessary to develop a new method to evaluate the repeatability and the accuracy of micro-assembly process.

A. Relative characterization of assembled MOEMS

There are two types of characterization:

- the relative characterization, which consist in measuring the position of assembled micro-object compared to system measurement,
- the absolute characterization, which define the position of assembled micro-object to a reference, for example a substrate.

In this paper, the relative characterization is carried out by a laser sensor which measure distances and linear displacements. The holder is assembled on the substrate and scanned with the laser sensor thanks to the linear displacements (X_1, Y_1, Z_1) of the NanoCube (100 μm of stroke and 1 nm in resolution with closed-loop control). Due to the positioning error of the holder, its pitch and its yaw have an influence on the reflection of a beam whereas this is not the case of the roll. To determine these two angles, a 3-D group of dots corresponding to the micro-object surface is obtained.

The first coordinate comes from the laser measurement according to X axis. The two other coordinates come from the displacement of the NanoCube according to Y and Z axis. To determine the plane corresponding to the micro-object surface, the method is based on a principal component analysis (PCA). From points of this plane, the PCA will then find the best axis of projection to get a one-dimensional

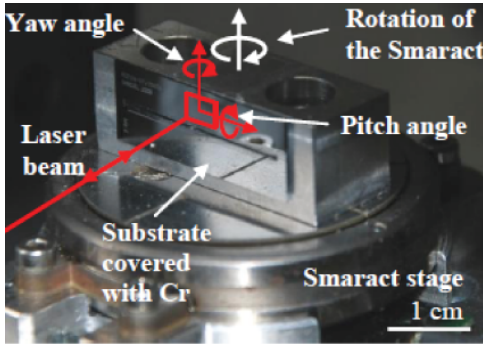


Fig. 7. Setup for the validation of the measurement method.

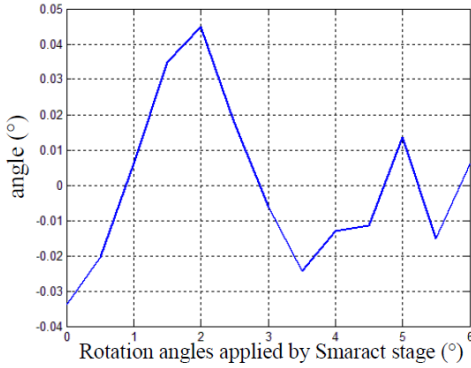


Fig. 8. Error between applied and measured angle.

representation of the groups of dots. Afterwards, the equation of equivalent plane is defined by equation 1.

$$ax + by + cz + d = 0 \quad (1)$$

a , b and c are the coefficient director of the plane, d is a constant. Pitch and yaw are calculated respectively by equations 2 and 3.

$$\alpha = \text{sign}(b) \cdot \arccos\left(\frac{\vec{u} \cdot \vec{N}_1}{\|\vec{u}\| \|\vec{N}_1\|}\right) \cdot \frac{180}{\pi} \quad (2)$$

$$\beta = -\arctan\left(\frac{c}{\sqrt{a^2 + b^2}}\right) \cdot \frac{180}{\pi} \quad (3)$$

\vec{u} is the vector (1,0,0) and \vec{N}_1 is a orthogonal vector to the plane.

We perform the validation of the developed method by introducing the yaw angle by a rotation stage based on SmarAct SR-3610-S ($3 \mu^\circ$ in resolution) as seen in FIGURE 7. We compare the measured angle with the introduced angle. The results are presented in FIGURE 8 which shows the error between applied and measured angle. Measurements are made with a mean of 5 squares (sides of $80 \mu\text{m}$) and provide an accuracy better than $\pm 0.04^\circ$.

Thus, this method can be used to measure pitch and yaw angles of assembled holders (see FIGURE 9), but also the square centre position.

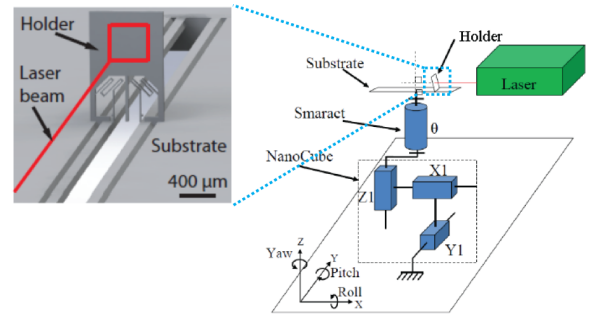


Fig. 9. Principle of angles measurement based on scanning surface.

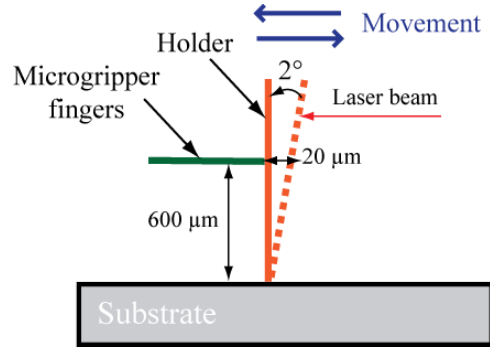


Fig. 10. Principle of the disruption application.

B. Effect of flexible parts after an assembly

This experiment aims to estimate if the spring stiffness of holders is adapted for the assemblies (validation of the design). Spring being used to maintain the holder position, the principle consists in pushing the holder with one of the microgripper fingers and moving back as far as the initial position. The contact is approximately established at $600 \mu\text{m}$ from the holder basis and on the vertical axis of symmetry of the holder. The pushing is of $20 \mu\text{m}$ after the contact which creates a deviation of 2° as shown in FIGURE 10. The holder is covered by a gold layer for improving reflectivity. The operation is repeated 6 times by entering the values of displacement of the microgripper in a control panel. The silicon holder is a mirror covered by a gold on the scanned face. The NanoCube (Y_1 and Z_1) moves in square form every 8 seconds thus a point on the graphs is a mean of 8 measurements.

For each disruption, pitch and yaw are measured with less than $\pm 0.03^\circ$ of the standard deviations and less than $\pm 0.04^\circ$ angle variation (see FIGURE 11). The displacement of the holder is measured less than $0.6 \mu\text{m}$ after each disruption. Finally, this experiment confirms that the stiffness of holder springs is well suited : it is not too stiff for the microgripper in the YZ plane and it is enough stiff in others planes (XY and XZ plane) for assemblies since holder comes back to a stable and repeatable position after disruption.

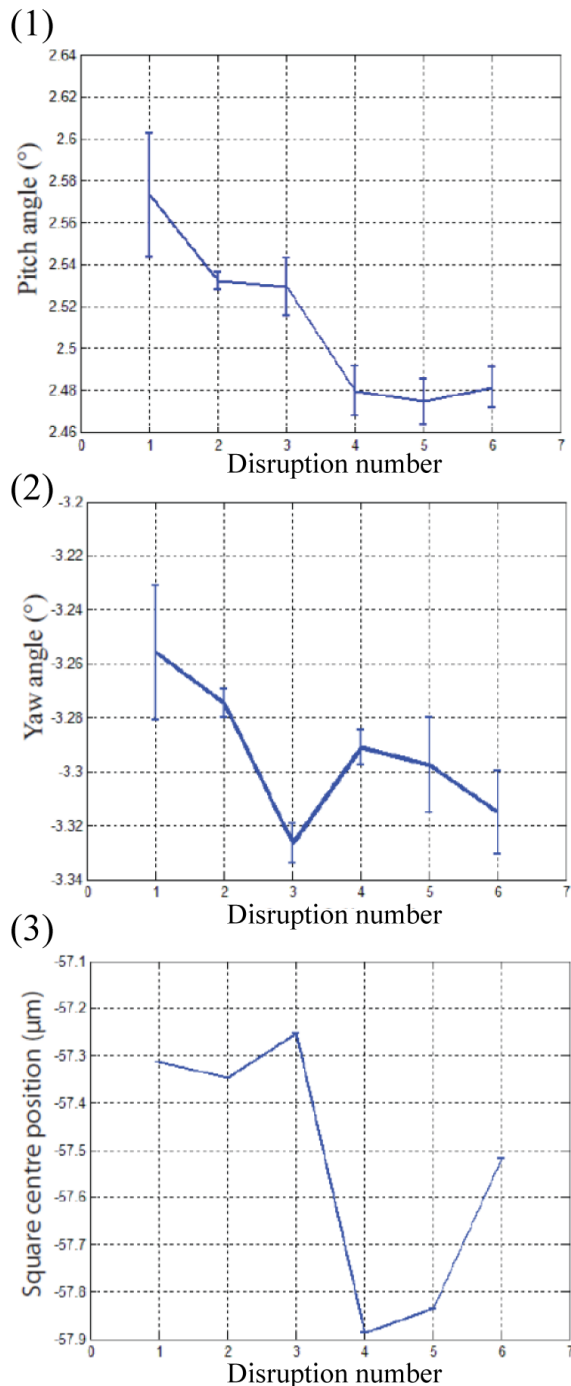


Fig. 11. (1) Pitch, (2) Yaw angles and (3) square center position measurements after disruptions.

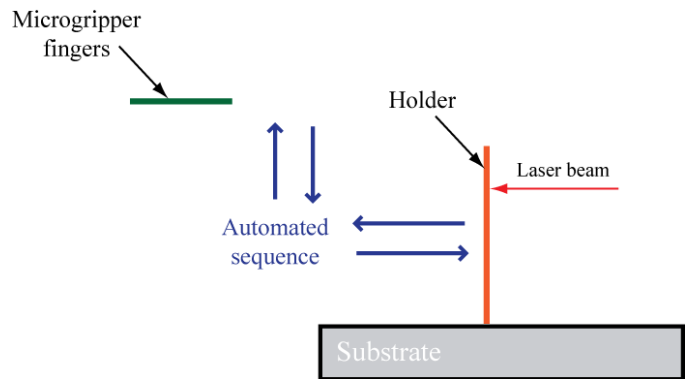


Fig. 12. Automated sequence of assembly and disassembly for repeatability study.

V. CONCLUSIONS AND PERSPECTIVES

The reconfigurable silicon free-space micro-optical bench, presented in this paper, provides a generic approach towards a new generation of complex MOEMS. It can be used as a tool to build proof-of-concept demonstrators or to characterize new micro-optical components. We have proposed a concept, fabrication of holders and substrate, and then validated it with some assembly results. The characterization method is proposed. The developed measurement method with laser sensor indicates that the tilt of assembled holder can be determined with sufficient accuracy better than $\pm 0.04^\circ$.

The effect of flexible parts after assembly has been studied by introducing disruption and measuring pitch angle, yaw angle and the square center position. For two angles, less than $\pm 0.04^\circ$ standard deviation has been measured and the displacement of the holder is less than $\pm 0.3 \mu\text{m}$.

Automated sequences of assembly and disassembly (see FIGURE 12) have to be studied to investigate the repeatability of the assembly process which integrates the robotic micro-assembly and RFS-MOB system repeatability.

Some investigations have to be performed for absolute characterization in order to measure accuracy of the assembly. The integration of the absolute reference, like high quality hole, can be done on the substrate as shown in FIGURE 13.

The obtained results constitute an important step before repeatability and accuracy of the assembly process.

VI. ACKNOWLEDGMENT

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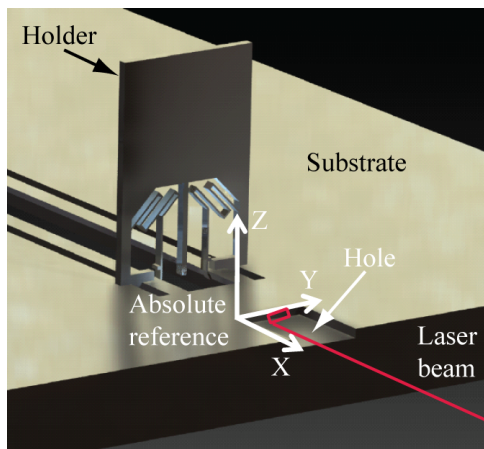


Fig. 13. Absolute reference integrated on the substrate for assembly accuracy.

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