Packaging investigation and study for optical interfacing of micro components with optical fibers – Part II

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(Recibido: 12 de febrero de 2007; Aceptado: 16 de mayo de 2007)

An investigation study concerning optical fiber alignment and micro-mirror performance in MOEMS devices is being reviewed in this paper. The central attention of the study is the analysis of optical fibers positioning, alignment, bonding, optical improvements, coupling to micro-lenses for beam collimation and waveguides. Also, we highlight features concerning coupling of optical fibers to micro-mirrors while searching for the proper alignment and characterization of the optical beam reflection, its tolerances, relative positioning, and attachment techniques. This Part II presents assembly procedures and experiments considering the first Part I of this work.

Keywords: MicroElectroMechanical Systems (MEMS); Packaging; Optical interconnects; OptoElectronics

1. Introduction

The encapsulation of MEMS optical devices is a big concern due that it usually represents around 70% of the total cost of the development / manufacturing of microsystem devices [1]. The quest towards the identification of cheaper and less costly encapsulation solutions are key for the release of new electronic products end services needing optimized and cost effective solutions [1-3]. In addition, a key pitfall in taking a semiconductor or MEMS devices from prototype to manufacturing would be the poor selection of attachment materials of interconnected layers, specially the encapsulation layers of the design [4]. This pitfall is commonly found in research institutions wanting to demonstrate a proof-of-concept prototype, where teams are not constrained by manufacturing issues. At prototype development stages, the device assembly configuration is often not revised in detail with regard to selections of attachment methods of interface layers of semiconductor and MEMS designs. Usually, the attachment / bonding methods may be determined by the chosen outsource manufacturer's capabilities without assessment of optimal interfacing in designs. This work presents a summary of an investigation study concerning attachment methods, materials, processes and assembly procedures to specifically attach photonic MEMS devices, including optical fibers into complete electronic devices.

The content of this paper is presented as follows. The first section of this work (paper Part I) considers general methods and processes for aligning and attaching optical fibers to a substrate, which considers direct aligning into silicon substrate, alignment through microlenses, connectors, optical waveguides, and hybrid approaches. We also address critical issues concerning the development capability to align and package optical fibers with small elements. Issues such as tolerances, lateral and angular misalignments, and attachment methods are considered in this section. Finally, critical issues related to insuring the reliability and stability of such packaging arrangement over time and temperature are highlighted. This second report (Part II) of this investigation provides the initial development of alignment and assembly procedures of optical fibers into Silicon chips in the CICTA Research Center.

This work was supported by Sandia National Laboratories, contract 9602, PO#659783 January-July 2007 [5].

2. Designs developed to align Optical Fibers to MEMS and other structures

Several designs were developed to align and fix optical fibers to Silicon substrates. The main design is shown in figures 5.1-3. These designs consist of placing the optical fibers in between two substrates arranged in a sandwich-like package. Figure 1.1 shows two silicon-machined parts of the main design. The lower part in figure 1.1 is also shown in figures 5.2; it has v-grooves as shown in figure to align the optical fibers, and its central section has a DRIE micro-machined region which can be used as a stop while aligning or inserting the fibers through the micro-machined v-grooved channels (refer to Figure 1.3b). The purpose of this design is not only to align optical fibers to a substrate, but also to hermetically seal this package, following approach from [6].

Cross sections A and B, and view C from figure 1.2 are shown in Figure 1.3, which also shows the upper substrate and a lead frame on top of cavity of upper substrate for hermeticity.

Several important aspects of this design should be highlighted here: 1) The Optical fiber should fit into the v-grooved channel (v-channel) but shall not be loose, since the purpose of the v-channel is to align the optical fibers 90° with respect to the edge of the central section of the lower substrate with the smaller possible resolution, as

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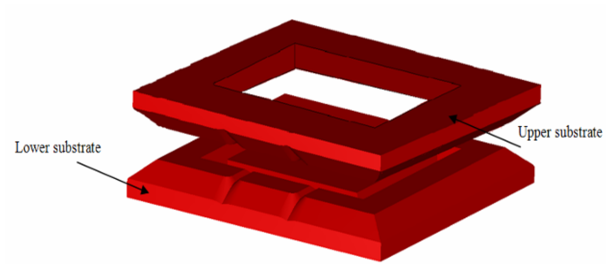


Figure 1.1. Design of two silicon micro-machined substrates for aligning Optical Fibers

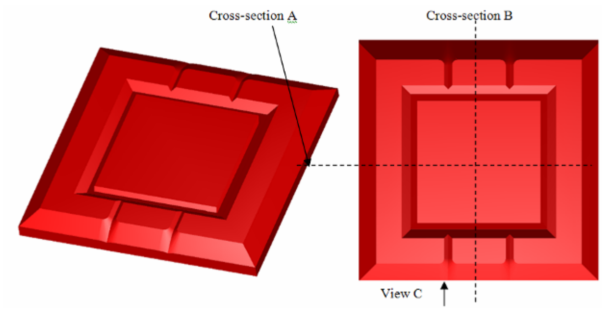


Figure 1.2. Design of lower substrate showing v-grooves on the sides and DRIE machined central section.

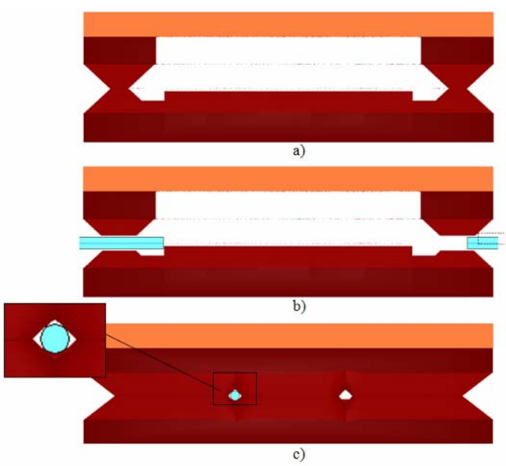


Figure 1.3. Cross sections of the main design showing the three main parts: lower and upper substrates, and ceramic lead. Sections a) and b) show cross sections A and B respectively, and section C shows view section C from Figure 1.2, considering final assembly with upper substrate and ceramic lead.

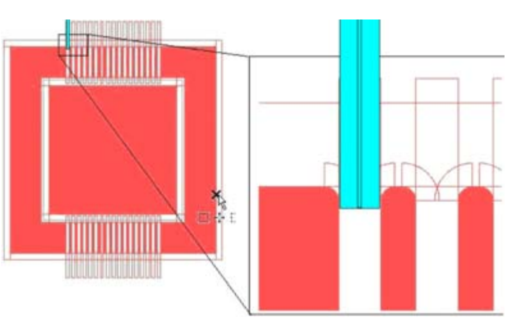


Figure 1.4. Layout of a lower substrate design showing rounded edges for better alignment assembly of optical fibers.

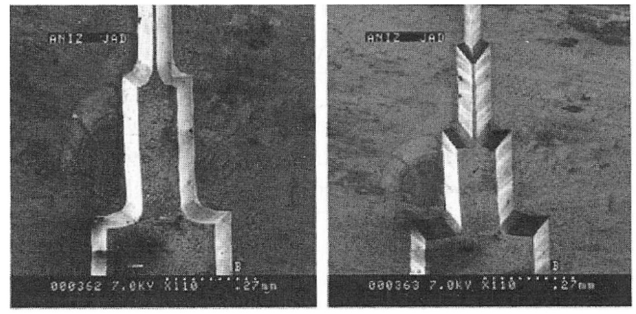


Figure 1.5. Smooth edges due to both rounded edges and no bulk etching from [7].

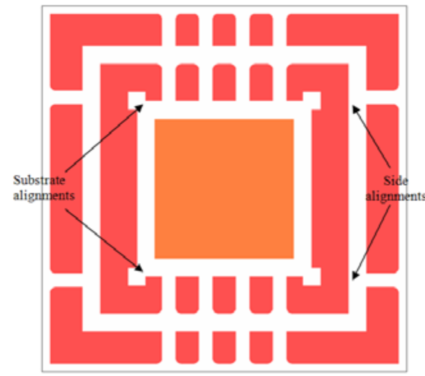


Figure 1.6. Layout design showing features: side alignment and substrate alignment.

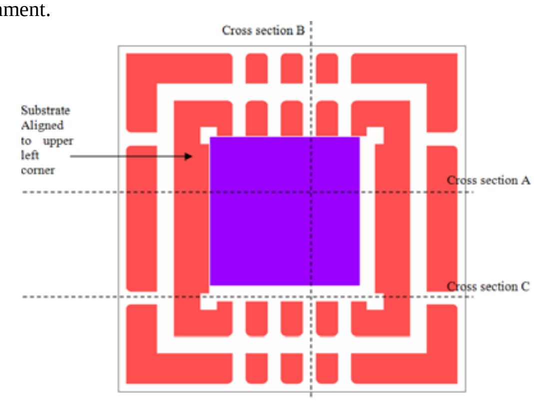


Figure 1.7. Layout design showing advantage of using substrate alignment features to accommodate and align substrates to any corner of the central opening.

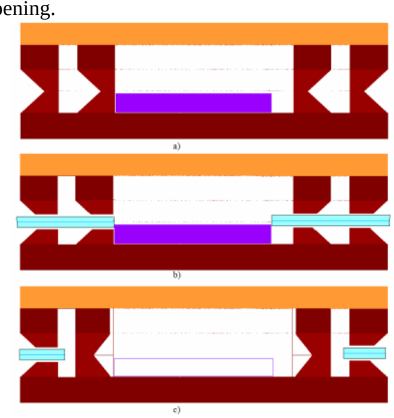


Figure 1.8. Cross section views of a design having substrate alignment features to support a thinner substrate in the center of the package.

shown in left section of part b from Figure 1.3; 2) the external v-grooves help in the assembly process while aligning the fiber through the v-grooved channel, as shown in the right section of part b from Figure 1.3; 3). The central section of the lower substrate should be DRIE machined to stop the movement of the optical fiber, if the assembly process allows contact of the fiber to the central section, or central substrate; 4) the height of the central substrate with respect to the join of the two silicon micro-machined substrates should be lower but not too low to permit the optical fiber to contact the edge, as shown in parts b and c from Figure 1.3; 5) The central substrate for this initial design is a dummy substrate, since the idea is to assemble, place and hold a separate substrate having micro-machined structures which might be aligned with respect to the incoming optical fibers; 6) Epoxy or metal sealing material shall be placed in between the v-channels and the fibers while looking for hermeticity to protect the internal microstructures.

Also, by rounding the edges of the layout of the lower substrate, as shown in figure 1.4, one can diminish the possibilities damaging the optical fibers while trying to assemble the fibers into the v-channels. Obviously, if one lets the bulk micro-machining process to run for longer amount of time (see figure 4.2), the edges will not be that smooth as presented by [7] as shown in figure 1.5.

A further advance in the design is shown in figure 1.6. If we define “contact ring” as the area where the upper and lower silicon micro-machined substrates make contact (are bonded), we can say that design from figure 1.6 has two contact rings. This is, the red layout corresponds to the contact/bonded area of the lower and upper silicon substrates. The orange layout in the same figure 1.6 can be the center substrate. Two features are included in this new design, the substrate- and the side-alignment features.

The side layout designs in figure 1.6 are required to align the upper to lower substrate by placing two dummy optical fibers on each side. This is a similar approach to that followed by [8]. Notice that side alignment features and dummy fibers might not be required if lateral v-grooved channels are fabricated on the vertical features in both rings. This is, layout features from figure 1.6 only considers fibers coming in from upper and lower part of the layout.

The substrate alignment features are required to allow alignment positioning of a substrate to the corner of any of the four sides of the central opening (figure 1.7), assuming no central dummy substrate feature is left in the lower substrate. Cross section views from figure 1.8 show an aligned substrate while using substrate alignment features to support the thinner substrate in one of the corners of the package

3. Fabricated Fixtures and Structures for holding and fixing Optical Fibers

We fabricated and machined testing structures for the designs presented in section 5.1, including micro-machined silicon substrates and fixtures, micromachined fibers, as well as two assembly setups (type A and B). The assembly setups consisted on a Signatone Probe Station, a Newmark micro-manipulator, a PI nano-poitioner, and stereo zoom optical systems with 2.0 USB color cameras and monitors. The assembly setups are shown in figures 2.1 and 2.2.

The setup type A is a setup consisting on one Newmark XYZ-θ micro-manipulator (figure 1.10) with resolutions down to 1-2 micron resolution on each axis, and 0.05 degree resolution in the rotational axis, a PI XYZ nano-positioner with resolutions down to 1-2 nanometers on each axis, two stereo zoom optical systems with one 2.0 USB and one S-video color cameras, two monitors, and a computer with a house made computer system interface for controlling the micropositioner and the nanopositioner. We first investigated the assembly processes with this setup type A but the outcomes were not as satisfactory as expected, as explained in section 5.3. But, this system is good enough for assembly processes down to +/- 10 microns resolution.

The setup type B is a setup consisting on one Signatone Probe Station model 1160 with one 2.0 USB color camera and objectives 10x, 20x, 100x (shown in lower sections of figure 2.2), the Newmark XYZ-θ micro-manipulator (shown in figures 2.1 and 2.2), the PI XYZ Nanocube nano-positioner (shown in upper section of figure 2.2), one stereo zoom optical system, one two monitors, and a computer with a house made computer system interface for controlling the micropositioner and the nanopositioner. In order to build up setup type B, we had to disassemble the probe station and take the plate out of the base, to incorporate the micropositioner, nanopostioner and a lateral video zoom system.

Figure 2.3 shows the assembly setup system B developed for this project. Figure 2.4 provides more information about the Degrees Of Freedom (DOF) and viewing capabilities of this setup.

Figure 2.4a shows the three DOF (XYZ) of the microscope (XY axes are coarse movements, and Z axis has coarse and fine positioning used for focusing); figure 2.4b shows the different objective power of the signatone prober; figure 2.4c shows the horizontal positioning of the target through a lateral view of the X-Z axis and from the Y axis; a coarse X,Y movement shown in figure 2.4d; a semi-fine four DOF XYZθ movement using the micropositioner shown in 2.4e; and the fine three DOF XYZ of the nanopositioner.

Due to the limited fabrication resolutions at INAOE, we sent a first prototype for the lower substrate from the designs shown in figures 5.1-3, as shown in figure 2.5.

We received from INAOE the first fabricated prototypes machined in a 3” wafer containing several lower substrates. Professor Wilfrido Calleja from INAOE was in charge of the fabrication stages of these prototypes. Figures 2.6 show a) four corners of four lower substrates, and b) a 25 microns diced cut in between the substrates from left and right.

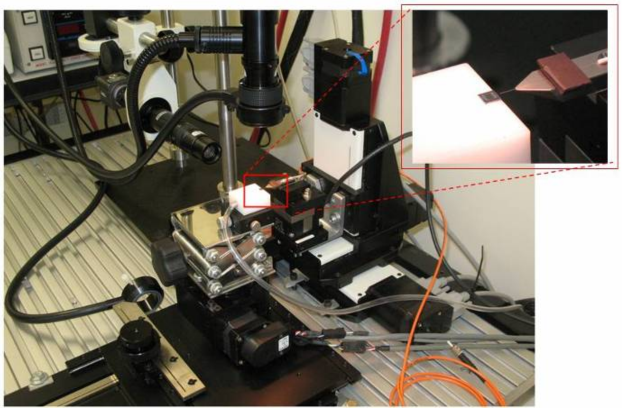


Figure 2.1. Assembly setup type A, including a Newmark micro-manipulator, a PI nano-positioner, and stereo zoom optical systems with 2.0 USB color cameras and monitors.

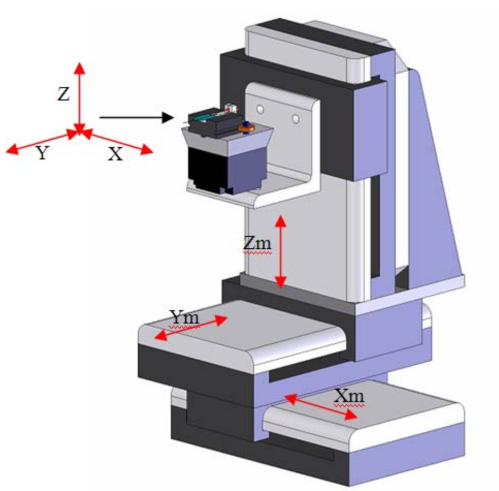


Figure 2.2. Newmark micro-manipulator showing the XYZ driving axes for nanoscale semi-fine micron resolution movement (no motors/encoders are shown in this drawing), and a PI nano-positioner mounted over Z axis of micropositioner, and showing the X,Y,Z driving axis for nanoscale fine movement.

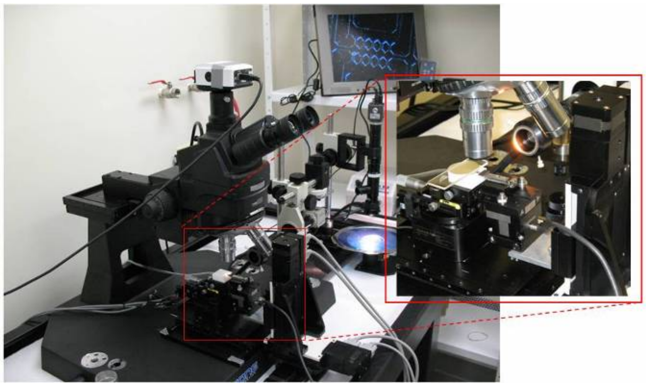


Figure 2.3. Assembly setup type B, including a Signatone 1160 probe station, a Newmark micro-manipulator, a PI nano-positioner, and stereo zoom optical systems with 2.0 USB color cameras and monitors.

4. Experiments developed for Aligning Optical Fibers

The experiments developed while aligning optical fibers to substrates are shown in this section. The procedure for aligning the optical fibers was as follows:

1) The optical fiber is prepared for assembly (to ensure proper polish end tip and cleaned). Isopropyl Alcohol or Acetone can be used for cleaning the optical fiber surfaces, the fiber is submerged in the solvent (Alcohol or Acetone) and wiped up with soft BCR swabs which leave no residues over the cleaned surface. Following this procedure we ensure a good cleaning for less coupling loss.

2) The optical fiber is mounted over the fixture positioned over micropositioner- nanopositioner setup (taking care of not damaging the end tip of the fiber); As mentioned before, the fabricated fixtures were developed to get a better optical fiber handling on the micro- nano-positioner, these fixtures can handle quantities of 1 up to 5 optical fibers at once. Figure 3.1 shows one of the fabricated fixtures (having five channels). The optical fiber end tip is retained at the silicon fixture which is attached to a metal base, and a low strength magnet is used to maintain the optical fiber over the silicon fixture

3) The assembly setup is prepared by means of using the lowest magnification objective to align the substrate with respect to the direction of the micropositioner-nanopositioner that holds the optical fiber (mainly, the micropositioner is used to approximate the fiber to the substrate, while at the same time the substrate is rotated to align its edge to the fiber, see figures 3.3).

4) By manipulating the micropositioner, the optical fiber approximates to the v-grooved substrate to get the fiber close to the edge of the substrate (about 50 microns.) In the assembled setup shown in figures 3.4 we used a horizontal positioned optical zoom to monitor the distance between the optical fiber and the substrate surface (as shown in figure 3.4a). This setup allowed us to approximate the optical fiber close enough to start the nanopositioner driving (which has a maximum range of 100 microns).

The developed user interface of the micropositioner allows a fast approximation to the target using scroll bars for the X,Y and Z direction displacement, and a fourth degree of freedom which is θ rotation of the chuck where the substrate is placed over. Also the micropositioner can make more accurate movement using the segmented displacement with a resolutions down to 1 µm, and rotation angles small as 0.001º. This user interface is part of the control program developed with Microsoft Visual C# shown in Figure 3.5.

5) Once the optical fiber is close to the substrate, the magnification of the objective is increased to have a closer look of the end tip of the fiber with respect to the position of the substrate. Increasing the magnification allow us to see small displacements and therefore maneuvering the nanopositioner more efficiently.

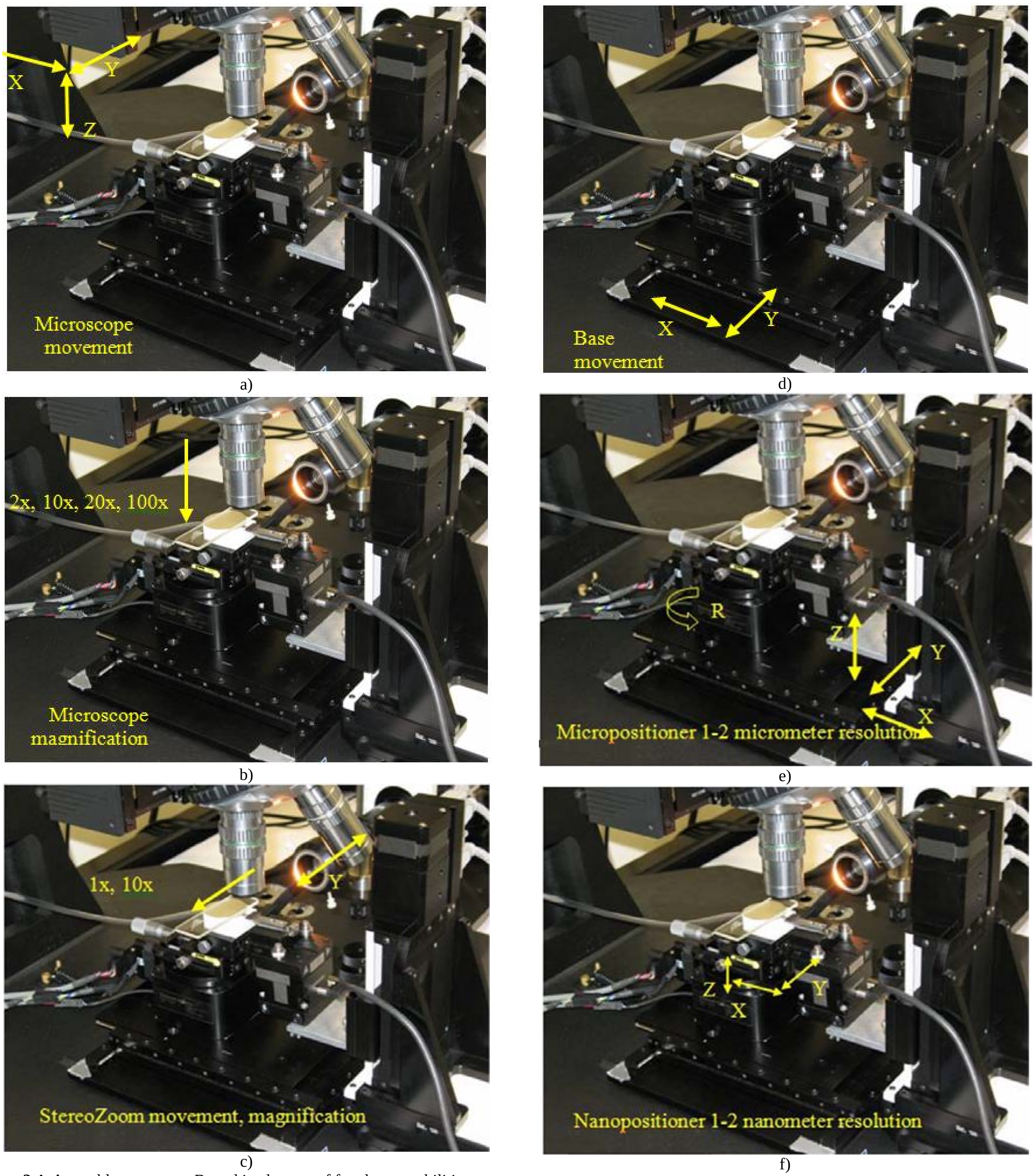


Figure 2.4. Assembly setup type B, and its degrees of freedom capabilities.

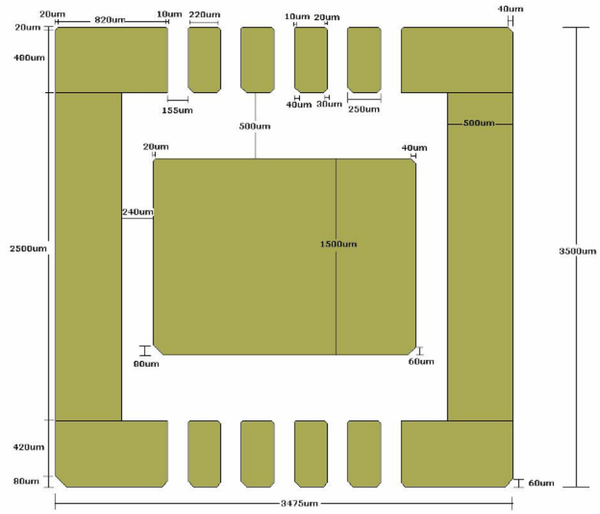
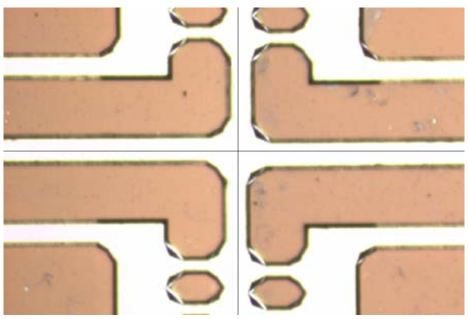
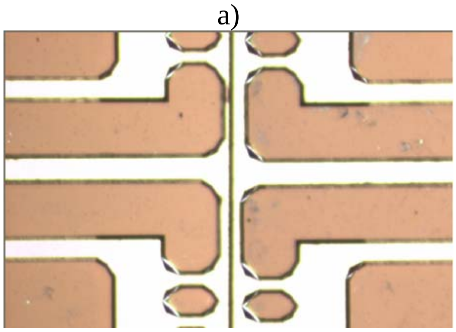


Figure 2.5. First prototype layout fabricated in INAOE.



a)



b)

Figure 2.6. Fabricated structures: a) four corners of four lower substrates, and b) a 25 microns diced cut in between the substrates from left and right substrates.

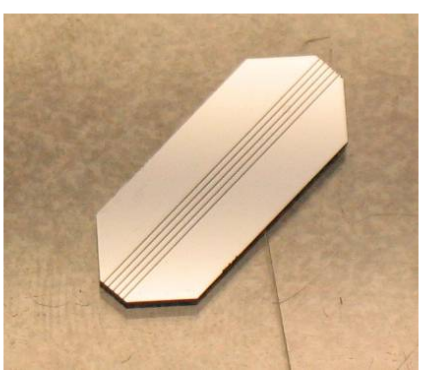


Figure 3.1. Machined fixtures using Disco dicing machine.

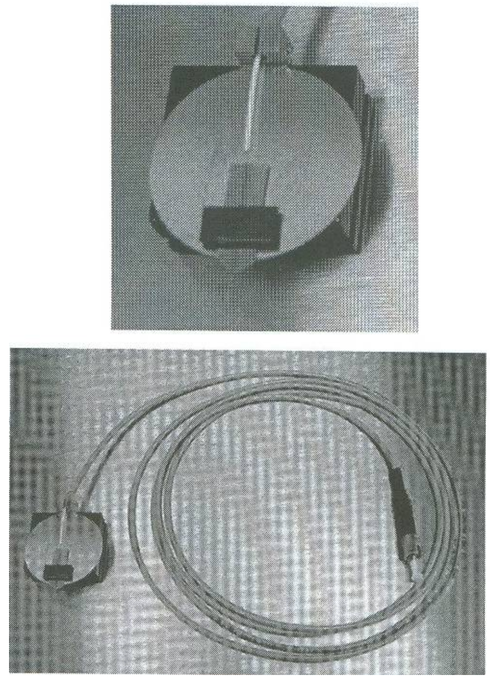
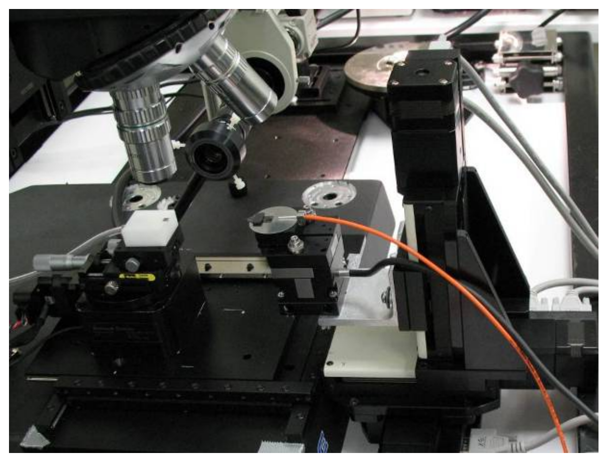
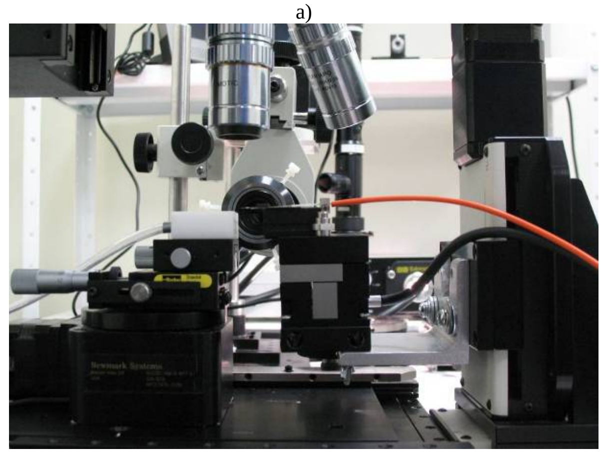


Figure 3.3. Optical fiber mounting over silicon fixtures assembled to nano/micro positioner devices.

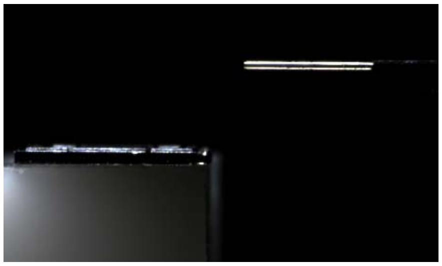


a)

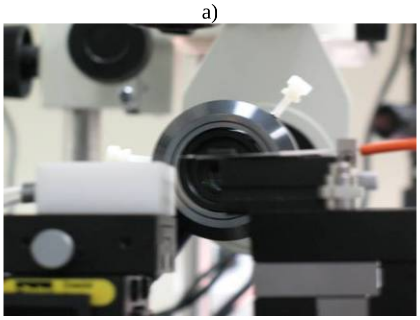


b)

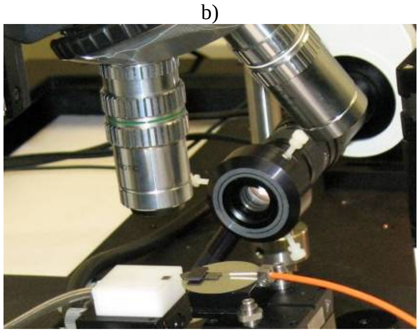
Figure 3.3. Optical fiber approximation to substrate through driving the micropositioner.



a)



b)



c)

Figure 3.4. Optical fiber approaching monitored by a horizontal optical zoom.

a)

b)

Figure 3.5. Visual C# User Interfaces for (a) Micropositioner and (b) Nanopositioner.

Also, with this procedure we can begin taking images and measurements required to perform a good optical fiber alignment. Figure 3.6 shows a v-grooved substrate and an optical fiber both machined with the dicing Disco machine. Notice in figures 3.6 that the v-groove edge in front and perpendicular to the direction of the optical fiber was diced away, to obtain a perpendicular wall in front of the end tip of the optical fiber (as shown in design sketch from figure 5.3b). Also, optical fibers used in some experiments had an angular cleaving over the tip of the fiber as shown in design sketch and several images shown in figure 3.7.

6) When the optical fiber end tip is close enough to the edge or aligning reference, the nanopositioner is used to develop fiber alignments with much more accuracy due to the resolution of this device. The nanopositioner has been one of the most important devices used in these experiments, it allowed us to perform very accurate positioning of the opotical fibers.

The nanopositioner has two user interfaces. One user interface is manual with analog control knobs (as shown in image with DC-OFFSET label from figure 3.8); it is a piezo-driven device, and the knobs are voltage driven offset channels to adjust the offset of the axis position. Also, the second user interface is a software based interface (Figure 3.5b) which drives a varying voltage using analog outputs in a DAQ from -2V to +12V which are amplified to higher voltages by the driver of the nanopositioner (amplifier shown in Figure 3.8 increases ten times the incoming voltage from DAQ).

7) Now the fiber has been aligned at the desired position, the measures can be done using digital image acquisition software which can be calibrated using same magnification of the pictures to be measured.

The cameras used on monitoring our experiments are distributed with software designed to measure and store pictures and screenshots digitally. We used the software DMP 1000 which can be calibrated using a calibration scale also called stage micrometer shown in Figure 3.9. This stage micrometer has a minimum resolution marks separated 20 microns, as shown in figure 3.10; the procedure to calibrate the software is by using the same magnification in the microscope, one takes a picture of the scale marks and then introducing the value of the segment to the software. In case there is no scale or the minimum segments (.02mm) cannot be pictured due the magnification used taking the picture, one can introduce a measured value of any detail appearing in the picture, with known dimensions to calibrate the software measurement tool.

Once the calibrations are done, you can measure any detail in the picture (segments, angles, diameters, etc.) by making a point selection of the detail being measured, this procedure is demonstrated in Figure 3.11.

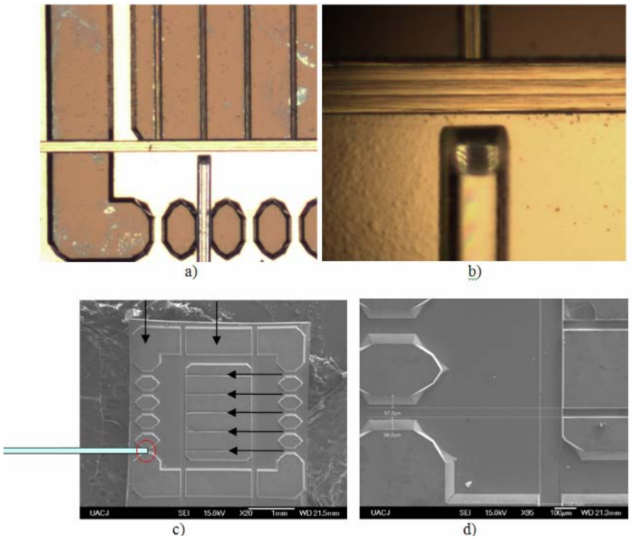


Figure 3.6. Zoom magnification for monitoring enhancement, a) Cleaved optical fiber over silicon substrate at 2X magnification, b) Same cleaved optical fiber over silicon substrate using 10X magnification, c) SEM image of diced substrate showing the direction of the diced grooves and a fake optical fiber highlighting in red oval the place of interest for assembly of fiber and edge of diced substrate; and d) a closer look to the interest region with dimensions.

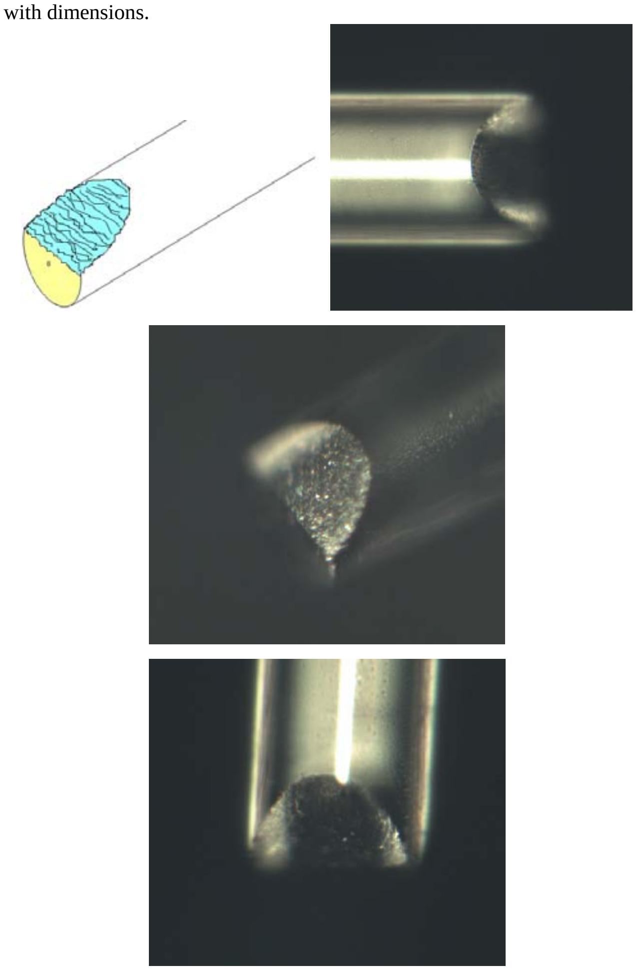


Figure 3.7. Optical fiber with diced tip, i.e., non-polished angular ends.

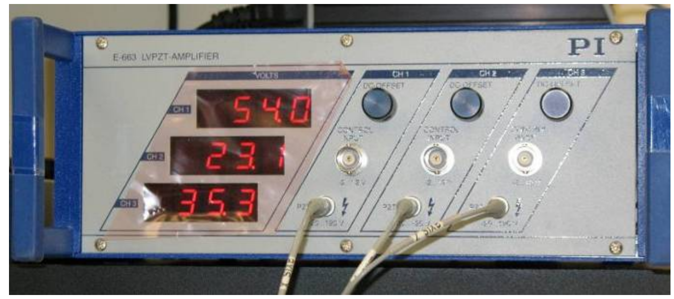


Figure 3.8. Nanopositioner Driver with manual analog inputs.

Figure 3.9. Stage Micrometer KR-814.

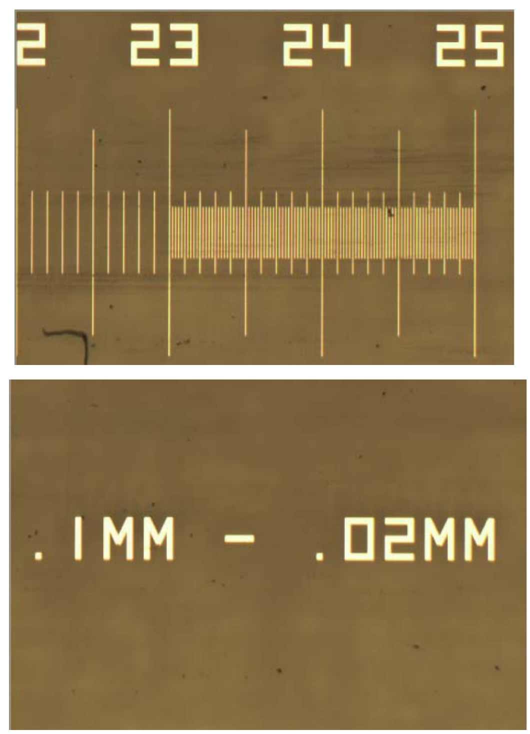


Figure 3.10. Stage Micrometer KR-814 (2X magnification).

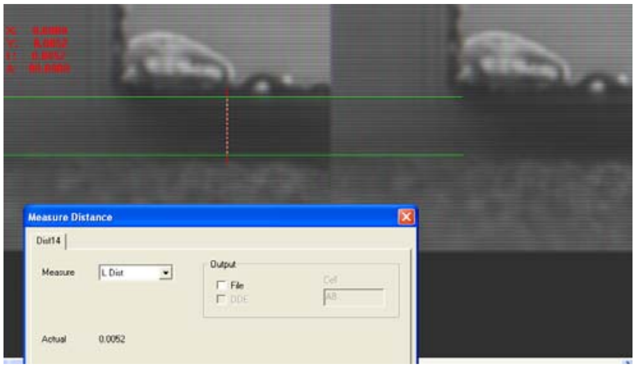


Figure 3.11. Measurement of the gap between a cleaved end tip optical fiber and Silicon substrate surface edge (100X magnification).

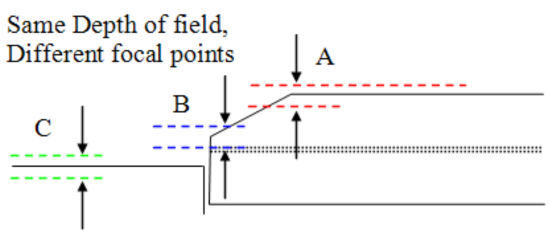
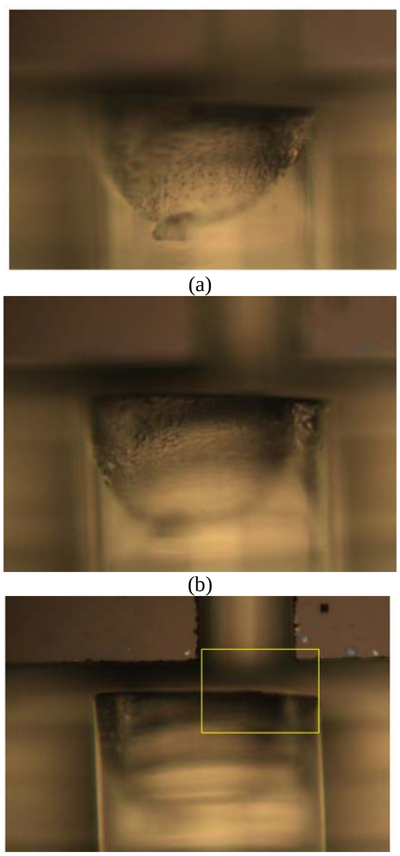


Figure 3.12. Optical fiber showing different focal points (A,B,C) of fiber-substrate using same depth of field.



(a)

(b)

(c)

Figure 3.13. 20x view of an Optical fiber with non-polished ends and different focus positions (A,B,C), corresponding to depth of fields shown in figure 3.12.

4.4 Resulting measurements and alignment accuracy of fabricated assemblies

Following the procedures from previous section, we show next some images presenting the initial experiments we developed, while looking for the best alignment approach. We first tried a cleaved fiber as shown in figure 3.12, while investigating for the depth of field of the system. This fiber allowed us to properly focus to different parts of the tip of the fiber, and the calculates depth of field was approximately 20 microns only. The views of the optical fiber that does not have a perfect end-tip, neither perfect angular diced side is shown in figure 3.13.

Images shown in figure 3.14 show a closer look using a 100x objective and looking into the highlighted section shown in figure 3.13c. Figure 3.14a shows un upper view of the non-perfect cleaved face of the fiber, 3.14b shows a closer look into the edge of the fiber, and 3.14c shows the focused view of the substrate, but not the edge of the fiber, since there is a difference on focal position.

The following experiment uses the approach shown in figure 3.15, where the end tip of the fiber (with non-perfect polished sides) was aligned to the edge of a substrate and both the substrate and the edge of the tip were in the range of the same focal point and same depth of field. The images from figure 3.16 show a 20X magnification of a cleaved end tip fiber reaching the edge of the inner surface of a substrate, straight edge provided by the cleaving at the tip allow us to align and measure easier and more accurate the fiber to the substrate in comparison to a normal end tip optical fiber.

The images from figure 3.17 and 3.18 show a 40x and 100x magnification of a cleaved end tip fiber reaching the edge of the inner surface of a substrate, straight edge provided by the cleaving at the tip allow us to align and measure easier and more accurate the fiber to the substrate in comparison to a normal end tip optical fiber. Figure 3.17 shows a separation of 10, 8, 5, 3.5, and 0 microns apart from the edge of the substrate. The measurements are estimated to have a +/- 0.25 microns of error, due to visual focus problems in the system. However, we have capability to control positioning of optical fibers with resolutions down to 0.05 micrometer (will send an addendum showing these results), the limitation is the visual feedback through the microscope objective.

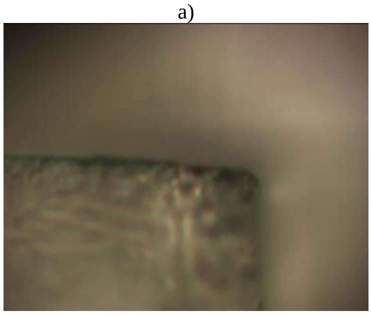
Figure 3.19 shows an optical fiber being manipulated through the v-channels of the manufactured substrates. Notice that the V-grooves help guiding the fibers even if more than 50 microns of misalignment exist.

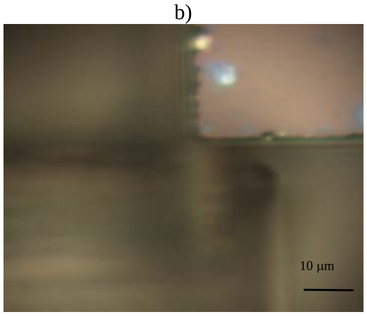
We also realized experiments dicing away entire sections of substrate by passing several times the dicing blade as shown in images from figures 3.20 and 3.21. Our purpose is to try to bond these structures with the substrate shown in figure 3.6c, so that we can experiment with desired outcomes expected from alignment designs presented in section 1. We plan to send an addendum to this report

Table 1 Assembly cost is driven by optical alignment tolerances [9].

Component Optical Alignment tolerance (µm)	Assembly Attachment Processing	Assembly equipment	Assembly time
< 1 µm	Special attachment methods & highly skilled process set-up	Custom & expensive	Slow
1 – 5 µm	Normal die attach processing	Flip-chip	Fast
10 – 20 µm	Normal surface mount processing	Std. surface mount automated pick and place equipment	Very fast


a)


b)



c)

Figure 3.14. 100x view of an Optical fiber with non-polished ends and different focus positions (A,B,C), corresponding to depth of fields shown in figure 3.12.

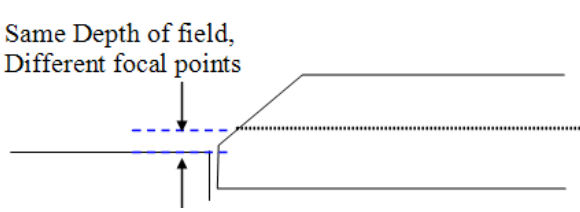
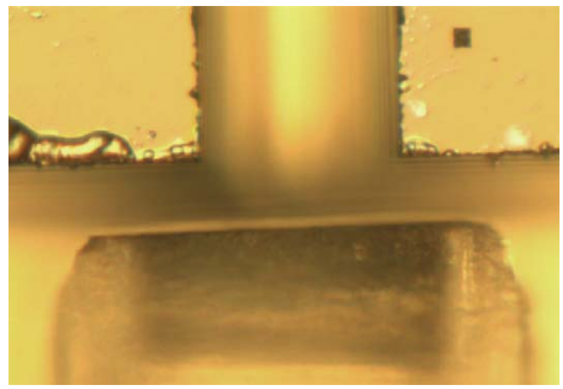
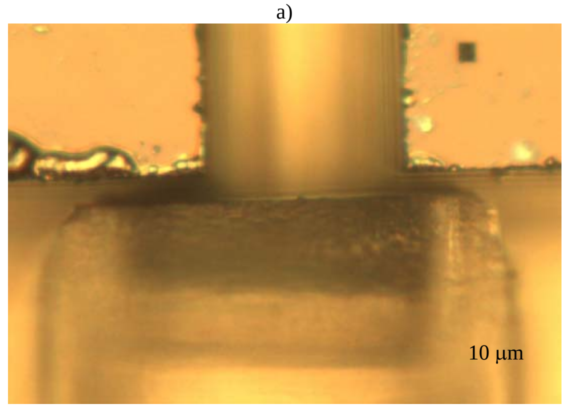


Figure 3.15. a) Optical fiber with non-polished ends, and b) different focal points (A,B,C) of fiber-substrate using same depth of field.


a)



b)

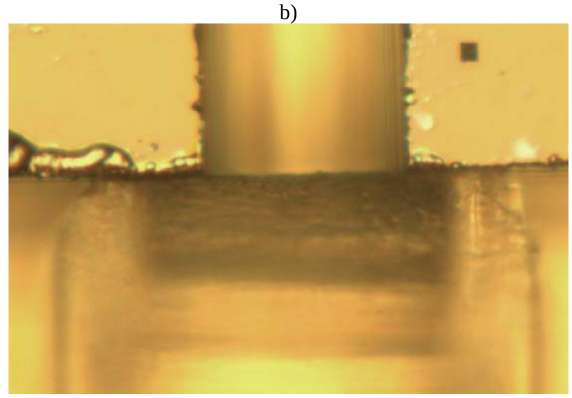

c)

Figure 3.16. 20x view of an Optical fiber with non-polished ends, and non-perfect cleaving manipulated to a) and b) close to the substrate edge, and c) in contact with the edge of the substrate

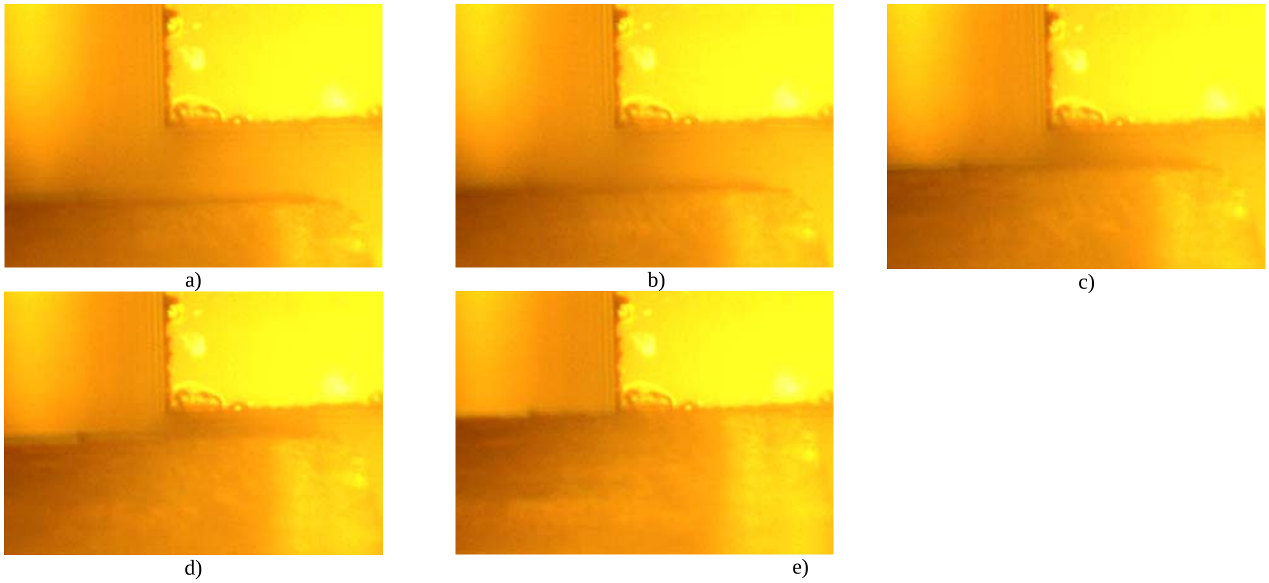


Figure 3.17. 40x view of an Optical fiber with non-polished ends and non-perfect cleaving manipulated to a) and b) close to the substrate edge, and c) in contact with the edge of the substrate.

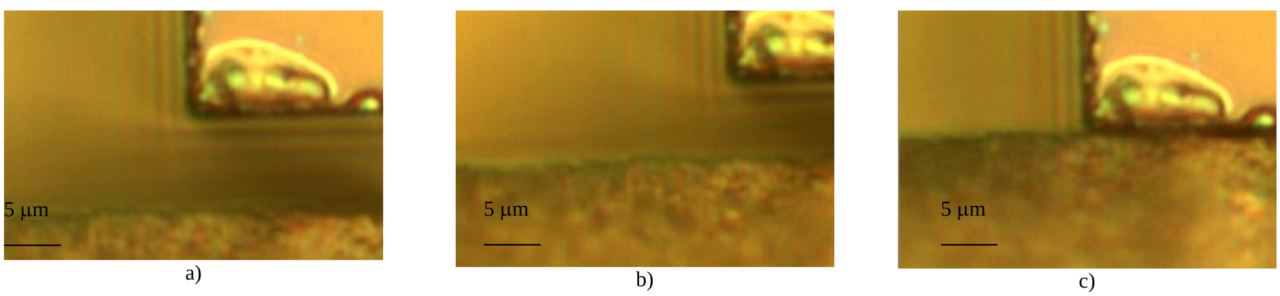


Figure 3.18. 100x view of an Optical fiber with non-polished ends and non-perfect cleaving manipulated to a) and b) close to the substrate edge, and c) in contact with the edge of the substrate.

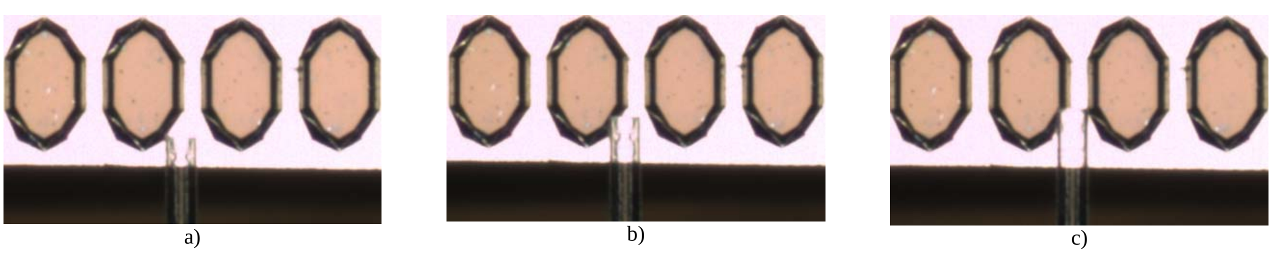


Figure 3.19. 2x view of an Optical fiber being manipulated through the v-channels. Notice that the V-grooves help guiding the fibers even if more than 50 microns of misalignment exist.

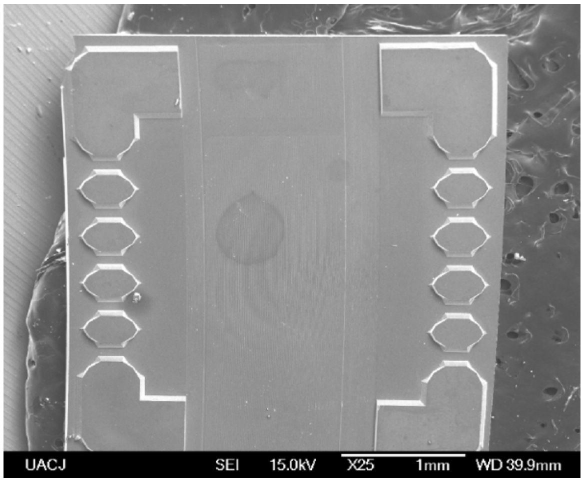


Figure 3.20. SEM image of diced substrate from up to down showing open apertures for assembling fibers from left to right.

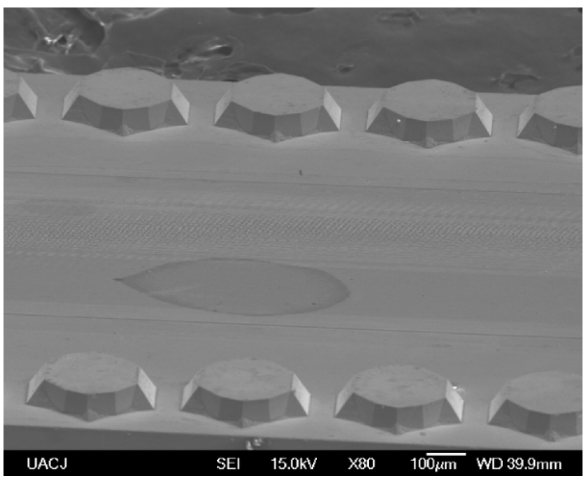


Figure 3.21. SEM image of diced substrate from side to side permitting assembly of fibers as shown.

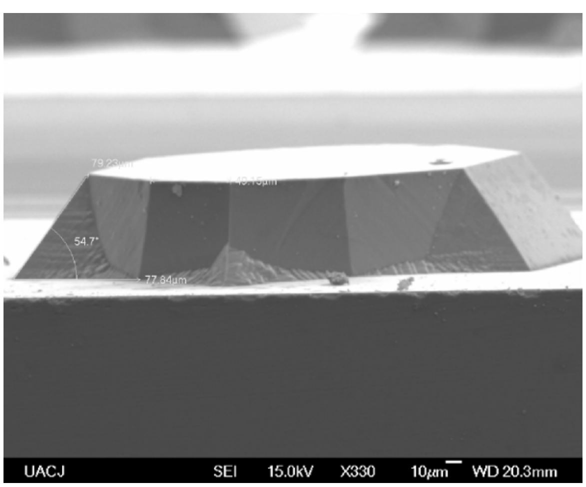


Figure 3.22. SEM image of etched substrate for v-groove machining. A clear over etching process is shown.

including the possible outcomes of the expected bonded substrates for better assembly results.

Figure 3.22 shows an over etching process of the micromachined v-grooves of the substrates received from INAOE. We will send this information to our colleagues as a feedback information to improve the outcome of a second fabrication process of double ring structures, as mentioned in section 1, and shown in figures 1.6-7.

5. Concluding Remarks

The initial part of this investigation was presented in [13]. Part II of the investigation reported design concepts to align optical fibers to MEMS and other microstructures, provides manufacturing and assembly results obtained from the experiments developed in this second phase of the investigation [5].

Considering the first part of this work (paper Part I), the main conclusion of this work is that if not collimated microlenses are used to perform active alignment to assemble optical fiber to micromirros, tight tolerances are required to adjust the orientation and positioning of the optical devices. However, if microlenses are used, relaxed positional tolerances can be obtained. Half sphere, GRIN and Ball lenses are the most common lenses used to collimate light coming from optical fibers to other devices such as micromirror structures.

Depending on the desired coupling loss desired, one can choose different submount, attachment, assembly, and positional technique (as described all over this document.) However, the main driver for decision perhaps is most of the time cost, and assembly time. Table 1 describes the summary of the consensus of all articles and documents investigated in this study. Basically, one can fall in three alignment tolerance categories: submicrometer, 1-5 µm, and greater than 10 µm, which categories depend mainly on the elected attachment technique and desired coupling losses.

For hermetic sealing of optical fibers attached to a substrate, several (costly) techniques require metallization for final assembly processes (commonly, Telcordia environmental requirements of photonics devices require such hermeticity.) However, E. Palen in [4] claims that one trend towards alignment and attachment of optical fibers is the use of the Impact Mount Technology, which eliminates the need of metallization on fibers [8-12].

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