Influence of Optical Probe Packaging on a 3D MEMS Scanning Micro-Mirror for Optical Coherence Tomography (OCT) Applications

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Abstract
An optical probe is developed for imaging in an optical coherence tomography (OCT) system. A 3D micro mirror is used for steering the beam from the source to the sample. A GRIN lens, fiber and micro mirror are assembled in a silicon optical bench. The assembled components are housed in the bio-compatible microinjection molded housing. The images obtained using this probe is studied with respect to probe assembly. Tolerance of GRIN lens placement, micro mirror placement on the substrate, deformation of the mirror, housing transparency and housing curvature are studied with respect to the final image from the probe. In this study it is found that a higher mirror curvature affects the depth of focus on the sample and mirror placement reduces the coupling efficiency during the optical assembly.

Introduction
Optical sensors are widely used in bio applications because of their non-contact nature. One important optical application in biosystems is imaging. Various different optical imaging techniques are available, which are limited by depth of penetration and resolution. Optical coherence tomography (OCT) is an imaging technique used to obtain high resolution cross-sectional images of microstructure in transparent and non transparent biological tissues [1-4]. The OCT setup is similar to a Michelson interferometer and has a reference arm and an incident (scanning) arm. In the incident arm the light falls on to the specimen and the reflected light is captured and processed for imaging. A probe is necessary to focus the incident light on to the sample and to collect the reflected light. The optical probe is a biosensor consisting of optical components and a scanning component, and is an integral part of the OCT system.

OCT systems have been used extensively in ophthalmology and cardiology applications [5-6]. One of the advantages of using OCT in imaging is the possibility of in-vivo imaging applications [6-11]. In the conventional OCT setup the probe used is large and hence imaging by in-vivo technique is quite difficult. The probe can be used as an endoscope so that the internal tissue imaging can be performed. Morphological changes in the internal organ’s tissue can be identified by changes in the images. Comparing an image of healthy tissue with the newly taken image can ascertain whether there is any abnormality in the organ.

In commercial applications there are two types of OCT system, a swept source OCT (SS OCT), where rapid scanning of narrow-band source spectra is performed, and in the second type, spectral domain OCT (SD OCT), a Fourier domain detection technique is used.

Fig.1 A schematic view of OCT set up with Optical probe

Miniaturized probes are required for OCT systems for in-situ in-vivo imaging application. Researchers are working on miniaturized probes with additional features to get complete imaging without rotating the probe. The probes are designed based on the type of application, either forward imaging or side imaging types. Forward imaging probes can provide tissue structural information such as image guided biopsy while the side imaging probes are suitable for imaging within a tubular organ such as gastrointestinal tract, urinary tract etc.[3-11]

The optical probe used for OCT systems includes a scanning component. In this novel probe approach, a 3D micro mirror is the scanning component and is used to scan the beam on to the sample for imaging [2]. Other components include in the probe are a GRIN lens and fiber (fig.1). In this optical biosensor probe a laser beam of wavelength 1300nm is used.

Probe design:
The probe is designed to meet the needs of in-vivo imaging applications. The reflected light from the sample is collected by a micro mirror. Light from a source is connected to a fiber which is aligned to a GRIN lens with specific focal length and numerical aperture depending on the penetration depth of the laser in to the bio sample (cancer tissue). The light falling on the 3D mirror is steered and focused into the
nearby sample. A depth of penetration of 3mm into the sample (cancer tissue) is targeted for this design. The reflected light from the sample is collected to the 3D mirror and in turn sent back to the GRIN lens and fiber to the image processing system.

A silicon optical bench is used to attach the GRIN lens, fiber and micro mirror. There are two substrates for the assembly: a top substrate and a lower substrate. In the top substrate the 3D micro mirror is attached and in the lower substrate the GRIN lens and fiber is attached (Fig.2). Probe housing with transparency at a wavelength of 1300nm is selected. The housing is designed to meet the micro injection molding process and provide optical and electrical interconnection to the micro mirror. A silicon mirror with diameter of 500 m in a 1.5mm chip is used in this probe (Fig.3). The mirror is suspended on 4 springs of 2 m thickness and is actuated by the thermal actuation method.

Optical Simulation:
The optical design is the most important part of the probe design. The imaging quality of the probe depends on proper design of the optical path and the components associated in the optical path. In the optical assembly an important criterion of performance is the optical loss, which is contributed from many sources. The main sources for optical loss are the coupling between the fiber and GRIN lens, the working distance from the GRIN lens to the micro mirror, the micro mirror roughness, the micro mirror flatness, the housing transparency and the radius of curvature of the housing etc.

An optical simulation is performed using Zemax software as shown in figure 4. In the model all the optical elements are assumed to be perfect so that there are no scattering phenomena. In the diagram the working distance is from the GRIN lens to sample mirror, (a+b). Fresnel reflection from all the surfaces are taken into account in calculation of optical loss obtained from the simulation. The single mode fiber is adjusted to be near to the spacer. The spacer is a glass component with a single refractive index similar to a BK7 glass. This component is considered to be closely attached to the GRIN lens so that air gap and surface transition between them is neglected (although in reality, there is a small gap that may be filled by transparent adhesive or air). In the model, on the exposed surface of the GRIN lens an anti-reflection (AR) coating is used to prevent back-reflection. The micro mirror deflects the light by 90° to hit the sampling mirror. A detector was superimposed with the sampling mirror. Maximum coupling efficiency achieved with this design is about 70%, considering all the losses in the joints.

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warp; it can be either convex or concave in shape depends on the stress during the process. This causes the micro mirror to have a certain curvature. Most of the mirrors produced are concave mirrors. Since the mirror shape is of concave nature it results in a reduced working distance. To understand the effect of a curved mirror on the assembled optical system, simulation was performed to find out the locations of the changed working distance and the coupling efficiency at the original (produced by a flat mirror) working distance (WD). Simulation results are plotted in Fig.5. From the result, it is found that the coupling efficiency decreases with increase of mirror curvature and drops exponentially when the radius of curvature of mirror falls below certain value, 160mm. From the plot, the curvature of the mirror has to be smaller than 0.66x10-2mm-1 (radius of curvature has to be larger than 152mm) to prevent the coupling efficiency from falling below 60%. Optimization of mirror design and process is in place to improve the curvature of the mirror.

From the results shown in Fig.6, it is seen that the percentage of reduction in working distance is linearly correlated with the curvature. Estimating directly from the plot, to maintain the change of working distance to be within 5%, the curvature of the mirror has to be smaller than 0.75 x10-2mm-1 (radius of curvature has to be larger than 133mm).

The micro mirror has an initial position that is laterally tilted 45° relative to the optical axis along the GRIN lens. Defining zero tilt angle as that when the micro mirror is parallel with the GRIN lens objective surface, positive tilt corresponds to directing the rays away from the probe as shown in Fig.7.

A simulation was performed to investigate the change in coupling efficiency when the micro mirror takes on different tilt orientations. A curved sample mirror is used so that maximum coupling can be obtained for all tilt orientations of the micro mirror and so that the sample point is always at the focal point.

From the results in Fig.7, it is clear that positive tilts result in more loss than negative tilts. The loss of optical power increases steadily while the angle of positive tilt is increased. On the negative half of the plot, there is no significant change to coupling efficiency when there is a change in the tilt. Optical Coupling study has done with angle of tilt +/-160 from the 45° mirror placement and found that there is a 10% coupling loss in the positive tilt while there is no significant drop in negative tilt. This means, the need for image compensation in programming is required only when the mirror directs light away from the probe, in the positive tilt.

Fig. 8 GRIN lens aligned to micro mirror

**Probe Assembly**

The lower substrate with the micro mirror is bonded with the upper substrate which has the GRIN lens and fiber. The micro mirror is attached vertically into the trench formed on the lower substrate. Solder balls are used to attach the micro mirror into the trench where the trace lines for power supply are formed on the side wall of the trench [1, 2]. The lower and upper substrates are optically aligned in an optical assembly stage before bonding together by UV cure method (Fig 8).

The housing of the probe is important for in vivo imaging applications. Since the wavelength used for illuminating the sample is 1300nm, the material used for the housing should have 100% transparency at this wavelength. Also the dimension demanded for this housing is less than 4mm; normal manufacturing methods are not possible to meet the requirements. The micro injection molding method is used to fabricate the housing of the probe (Fig.9). The probe size is a limiting factor for material selection, and also the wall thickness of the housing need to be controlled. A wall thickness of 0.2mm is used in this probe development. The
material used is a poly carbonate which has transparency of >95% for the wavelength of 1300nm. Since the probe length is about 25mm, a single micro-mold will provide additional stress to the probe and this will generate bending or warpage on the probe. In view of this, two molds are used to fabricate the housing of the probe. The closed tip part where the mirror is located is separated from the main body. They are joined together after the final assembly of the probe in the housing.

Assembly of the probe inside the housing is another important requirement in the final probe housing development. Since the probe requires power for mirror to rotate and the optical fiber is to illuminate the mirror with IR light, assembly of the probe in the housing needs to meet these requirements without damaging the probe. Special micro connections are used to connect the traces on the lower substrate which is connected to the micro mirror. The fiber is taken out from the probe housing using a special groove so that no big holes are left on the housing when the optical fiber and the power supply lines are taken out from the housing (Fig.10).

Probe imaging:

Imaging of the sample with the completed probe was investigated. It was found that the resolution of the image was not as good as with the conventional OCT set up. The reason for the lower resolution image is that not enough light is collected from the sample. The main factors contributing to this factor are the mirror curvature and the NA of the GRIN lens. The smaller the NA, the lower is the light collection efficiency. Another factor is the aberration of light due to the small curvature of the housing which slightly distorts the beam from the mirror to the sample, which eventually reduces the intensity of the beam.

Since the working distance of the beam is fixed, there is a change in the depth of the focus of the beam when the mirror starts scanning of the beam into the tissue. The shift in the depth of the focus of the beam affects the image axial resolution and in turn affects the image quality. Images have been acquired with a modified probe assembly and the image obtained is found to be comparable to that obtained with the commercial OCT set up. (Fig.11)

Fig.11 En face image obtained by a conventional optical microscope. (B) OCT en face image

Both en face and three dimensional OCT images acquired by the two axes MEMS scanning probe are shown in Fig. 11, 12. An IR viewing card (VC-VIS/IR, Thorlabs, United States) consisting of a transparent polymer surface and photosensitive material beneath the surface was used as an imaging target. As a reference image, an en face image in the IR viewing card was obtained by a conventional optical microscope with 0.75 NA objective lens and 550 nm light for illumination, which was shown in Fig. 11 (A). Fig. 11 (B) shows an en face OCT image of an arbitrary two dimensional plane in a relative small region of the IR viewing card with ~ 20 µm transverse resolutions and ~ 12 µm axial resolutions in air.

Fig.12 Orthogonal slices of OCT images acquired by the probe from IR viewing card
Conclusions

A miniaturized optical probe has been developed for OCT applications. Different packaging related factors which affect the image quality have been studied. It is found that micro mirror deformation affects the overall working distance and at the same time it affects the coupling efficiency. Images taken with probe are comparable with a standard OCT set-up and further improvement using image processing is ongoing. Some important results are summarized in the following.

1. A coupling efficiency of 70% is good based on the simulation and the images achieved with the current probe design using Grin lens and micro mirror.
2. The curvature of the mirror has to be smaller than 0.66\times10^{-2}\text{mm}^{-1} (radius of curvature has to be larger than 152\text{mm}) to prevent the coupling efficiency from falling below 60%. Lower radius of curvature affects image quality.
3. Mirror placement into the cavity of SiOB found that positive tilt contribute 10% reduction in coupling efficiency from the achieved value (70%).
4. There is no degradation in the image even with 95% optical transparent housing material.
5. The packaged probe has been assembled successfully with Grin lens, micro mirror in a microinjection molded housing of 4\text{mm} diameter with 0.2\text{mm} wall thickness using poly carbonate material.

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References:

2. C.S.Premachandran et al. “A biocompatible Miniaturized Package housing for a3D Micro mirror based Optical Bio-probe for OCT imaging application” Photonic West 2008 January
10. Tuqiang Xie, Huikai Xie, G. K. Fedder and Yingtian Pan “Endoscopic optical coherence tomography with new MEMS mirror” Electronics Letters, 16th October 2003 Vol.39, No.21