Chapter 6
SLM Fabrication

In order to perform an experiment into optical phase-only correlation it was necessary to fabricate an SLM to the highest standards possible. Chapter five has provided a background to the electronic operation of the 16×16 SLM and the liquid crystal light modulation mechanism used in this project. Actual fabrication of a working spatial light modulator is an extremely delicate process requiring a high degree of preparation and manual dexterity. One major difficulty in SLM fabrication is the accurate positioning of the glass cover cube over the VLSI backplane (referred to as the ‘chip’ in what follows), so that the fragile chip bonding wires are not damaged. Further, the glass should ideally lie absolutely parallel to the chip surface so as not to introduce a wedge into the liquid crystal layer.

This chapter details a review of previous fabrication techniques used within this Group. Experimental results using small test cells, rather than expensive packaged SLMs, point the way to a significant improvement in the fabrication process. One technique, known as ‘vacuum packing’ (section 6.2.2), works rather less well on an actual packaged SLM than on the test cells but still offers a significant improvement over the previous method.

1 Device Construction

Figure 6.1 depicts a cross-section through the assembled spatial light modulator. The final assembly process requires the affixation of an optically flat cube of glass over the pixel array at a precisely specified height. This is usually accomplished by the inclusion within the cell of 12μm thick polyester spacer strips cut by hand with a scalpel.

![Cross-section through an assembled SLM](image)

**Figure 6.1:** Cross-section through an assembled SLM

Traditional Preparation of SLM Components
It shall prove helpful to number the various assembly stages so as to avoid unnecessary repetition of those stages which are essentially unchanged in the new assembly procedure to be described shortly. This itinerary is essentially that used by Ranshaw, and describes the preparation of each component used in the assembly of the spatial light modulator.

1. The cover glass cube is cut with a diamond tipped saw from a sheet of optically flat glass. Each side of the cube measures 5mm, chosen to be larger than the active area of the chip and smaller than the distance between the bonding pads. See figure 6.2.

![Figure 6.2: Relative Dimensions of Chip and Glass Cube](image)

2. An indium-tin oxide counter electrode layer is then sputtered onto one face of the cube in an evaporation chamber, followed by a thin strip of aluminium along one edge of the same face and up the side of the cube so that a wire may be attached to make electrical contact with the counter-electrode.

3. An alignment layer of magnesium fluoride is evaporated onto both the ITO face of the cover glass and the chip surface. Both the chip and the cover cube lie at an angle of $60^\circ$ with respect to the horizontal as shown in figure 6.3. This results in microgroove formation on the surface of both components. Early alignment techniques also included light rubbing of a layer of polyamide with a felt pad to create the required microgroove structure with some success.

![Figure 6.3: Oblique Evaporation causing Microgroove structure](image)
4. A U-shaped spacer is cut by hand from a sheet of 12μm thick polyester, and placed over the VSLI backplane. The outer width of the spacer is 5mm and the inner width is 3mm. As the active area of the chip covers 3.2mm², most of the spacer material lies outwith this region, between it and the bonding pads.

5. A 2mm thick rectangular perspex guide is fabricated so as to lie on top of the ceramic carrier of the chip. A square hole 5mm on a side is cut in the centre of the guide to accommodate the cover glass.

**Traditional Assembly Technique**

1. Assembly takes place in a laminar flow cabinet so as to minimise the effects of atmospheric dust on the alignment layers, and begins with the placement of the U-shaped spacer upon the chip surface.

2. The perspex guide is affixed to the ceramic carrier with araldite epoxy resin.

3. A thin piece of wire is affixed to the top of the guide which will allow electrical contact to be made with the ITO counter electrode. The side of the glass cube with the evaporated aluminium strip is completely painted with electrocure conductive paint which forms a conductive pathway from where it will touch the wire to the counter electrode.

4. A drop of liquid crystal is placed on the centre of the chip with a syringe.

5. The glass cube is lowered through the guide, lightly clamped in place and secured again with Araldite epoxy resin. Electro cure paint is applied to join the wire of item 3 with the already painted cube face. When dry, araldite is also applied over this union to strengthen it.

A critical appraisal of these preparation and assembly techniques follows in the next subsection, and the finished SLM is shown in figure 6.4.

![Figure 6.4: Field Induced Birefringence Mode SLM constructed by Ranshaw.](image-url)

1.1 Motivation for Improved Construction Techniques

It should be noted that the assembly techniques devised initially by Underwood and, as described above, modified by Ranshaw were only intended to lead to a working SLM in Field Induced Birefringence (FIB) mode. Demonstration that the effect worked was sufficient for this purpose, so that only the most straightforward assembly procedures leading to this result were devised. Consequently, there exists a large scope for improvement.

One refinement in particular would reap the most reward, namely a technique whereby the uniformity of the LC layer is controlled with more precision. For the FIB effect the actual layer thickness of the liquid crystal is not critical, the optical path difference between two pixels being a function of applied voltage as well as cell thickness. In particular, let the effects of a slight wedge on the performance of a liquid crystal cell using FIB as a phase
Suppose both pixels are required to be in the same state, so that the optical path length (OPL) through the liquid crystal at both pixel locations is required to be the same. With the wedge in the LC layer, the OPL $\delta_i$ at each pixel is, ignoring the small effects of refraction, given by

$$\delta_i = \frac{2\pi}{\lambda} \int_0^{d_i} n_e(z,V) \, dz$$  \hspace{1cm} (1)

where $n_e(i)$ denotes the extraordinary refractive index of the LC at each pixel and $z$ denotes distance through the LC layer. It can be shown that the local refractive index $n_e(z,V)$ is, to a first approximation, a linear function of the local electric field, and is therefore only indirectly a function of the applied voltage across the cell. Setting the constant of proportionality to be $`C'$ gives

$$n_e(z,V) \approx C \frac{V}{d_i}$$  \hspace{1cm} (2)

so that the optical path length through the medium at pixel 'i' is given by

$$\delta_i \approx C \frac{2\pi}{\lambda} \int_0^{d_i} \frac{V}{d_i} \, dz$$

$$\approx \frac{2\pi}{\lambda} C V$$  \hspace{1cm} (3)

which is, to a first approximation, independent of the cell thickness.

This result further illustrates the usefulness of the FIB effect, namely that it is relatively insensitive to small non-uniformities in the thickness of the LC layer. Fabrication techniques should, however, endeavor to attain as parallel an LC layer as possible, as nematic LC cannot accommodate for the effects of large wedges in the cell.

SLMs using ferroelectric liquid crystal require a different drive scheme but the final assembly stages are as for the 16×16 device described here. As pointed out in chapter five, electro-optic effects relying on the faster ferroelectric LCs as extremely sensitive to the precise thickness of the LC layer. Research into the design of VSLI backplanes for very large (512×512 pixels) SLMs using such liquid crystals is well underway at this University. However, the area of final assembly is still problematic, uniformity of cell thickness being particularly troublesome.
The principal areas of contention with the assembly techniques are short and require little elaboration. They are listed here in no particular order and shall be further addressed in the next section.

1. **Poor Cleanliness of Assembly Environment**
   Airborne dust is always present to some extent, particle sizes ranging from the visible to just a few microns across. The effects of particulate contamination on the alignment of the liquid crystal are unquantified, though expected to be detrimental. This is because the cell geometry relies heavily on the alignment of the LC molecules at the cell boundaries. For a device with relatively large mirror dimensions such as the 16×16 SLM, small local misalignments within the confines of a mirror may cause little net harm compared to the larger area of correctly aligned molecules. Devices with smaller mirror dimensions are, however, liable to be more sensitive to the same scale of misalignment regions. Atmospheric cleanliness should be improved.

2. **Poor Cosmetic Appearance**
   As figure 6.4 shows, the fabrication procedure as a whole results in a device of very poor appearance. Alternative fabrication techniques should therefore try and improve the look of the final SLM. This has a practical aspect in that all SLMs can be assembled in the same way no matter what their pixel number. Current effort is directed to producing devices of a commercial quality.

3. **Water Vapour**
   It is known that the presence of atmospheric water vapour is detrimental to the operation of the liquid crystal. With the traditional assembly techniques, the liquid crystal is first put onto the chip and then the glass cube secured. It is difficult to see how any form of `de-gassing' (removal of H₂O vapour) can be effected at any stage of the traditional process.

4. **Uniformity of LC Layer**
   Although the spacer material should ensure a minimum thickness of 12µm, there is nothing to ensure that the glass cube lies absolutely parallel to the chip surface when it is glued into position. Figure 6.6 shows an interferogram taken of an SLM assembled by Ranshaw, under coherent illumination by He-Ne laser light at 633nm.

Once again it must be stated that no criticism of the originators of these assembly techniques should be inferred, indeed it is most probable that the points of contention raised in this section were well known to them both. I am indebted to both Underwood and Ranshaw for laying the foundations to this problem with which to build upon.

### 2 Test Cell Simulations

Initially the search for improved fabrication techniques centered upon finding a method which ensured the uniformity of the liquid crystal layer. In order that this be examined further it was decided to perform a series of
experiments using small test cells, the assumptions implicit in the traditional SLM assembly process may be transferred to the process of test cell fabrication.

The test cells used in these experiments comprise an identical cube of glass as used in the SLM assembly of the next section, placed upon an aluminium coated silicon wafer of the type used in VLSI construction. The wafer is known to be optically flat [63]. Each cube was cut from 'Ealing' utility grade optical flat with a diamond tipped saw, and is quoted as having a 1-3 \( \lambda \) (Na doublet) variation over 25mm\(^2\). The cube measures 5×5×6 mm with the smaller dimensions chosen to fit over the chip area, and the larger dimension of 6mm being the depth of the block. The optical quality was deemed sufficient for use in both test cells and spatial light modulator applications, bearing in mind the enormous price increase for even a slight gain in flatness. This increase was primarily due to the fact that `off the shelf' optical flats of greater quality tend to be thicker too, but a cube more than 6mm depth is undesirable, so that such glass would have to be custom made.

Flatness may be quantified most easily by using interference techniques, and to this end an interference bench was set up as shown in figure 6.7. The interference pattern resulting from the interaction of the beams reflected from the lower reflective silicon wafer and the glass / air-gap interface provides information as to the uniformity of the air gap thickness. For example, if a the air gap is wedged shaped the spatial separation between two maxima of the resulting fringe pattern is known to be \([\lambda/2]\) if the substrate is reflecting.

Figure 6.4 of section 6.1 has already shown an SLM assembled using the traditional technique, and the fringe patterns resulting from a non-uniform LC layer in figure 6.6. As fringes arise due to the non-parallelness of chip and cover glass, a reasonable proposal for their reduction, it is speculated, might be the application of light, uniform pressure upon the glass cube during assembly. The remainder of this section is primarily concerned with the details of such a procedure, beginning with a study performed using a mechanical method to apply the required pressure.

![Figure 6.7: Interference Bench Arrangement](image)

2.1 Mechanical Pressure Technique

A small perspex `assembly rig' was designed to hold both the glass cube and the silicon substrate in position while fringe observations were carried out. The rig was designed so as to allow maximum accessibility to the glass cube where it touches the silicon for reasons that will soon become apparent, and is shown in figure 6.8. A low, square indentation is cut into the base of the rig in which the silicon substrate is placed. This minimises the allowable movement of the substrate which might move spacers from their initial position. A smaller but much deeper square indentation (5mm on a side and 2mm deep) is cut into the lower face of the upper half of the rig to hold the glass cube. In both lower and upper halves of the rig, a round hole is drilled through the centre to allow investigation of the fringe pattern under various methods of cell fabrication.
The first attempt to improve cell uniformity centered upon mechanical control of the cell thickness. If four small nuts are gently screwed down on the threaded guide rods, it should be possible to adjust the height of the glass cube at each of its corners so as to make a uniform air-gap. Observation throughout of the interference pattern arising from the air-gap through the hole in the top of the perspex rig would provide the operator with an idea of which nut to turn and by how much.

This requires some practice, not least due to the small size of the nuts and spanner required, though was not the reason for the abandonment of this scheme. Figure 6.9 shows a photograph taken through one eyepiece of a binocular microscope of the view through the centre of the perspex rig during this procedure. (As such, and due to the depth of the hole in the top of the perspex rig, only part of the fringe pattern is visible.) The interference pattern suggests that the silicon wafer bowed under even light tightening of the adjustment nuts, and all attempts to eliminate the fringe pattern failed. Non-uniformity of the shallow guide indentation of the lower half of the perspex rig (into which the silicon wafer was placed) is the most likely explanation of the effect.

A FORTRAN computer program was written to study the effects of wafer bowing on the resulting fringe pattern. Figure 6.10 shows the fringe pattern expected when the square wafer takes on a 'sail' type shape. The wafer is modelled as if the four corners of the square are affixed to the perspex rig but the centre 'billows' out, with a height variation from the flat ideal given by

\[ h(x,y) = H_0 \sin\left( \frac{x}{\pi} \right) \sin\left( \frac{y}{\pi} \right) \]  

(4)
where $x$ and $y$ are scaled wafer coordinates specifying the fractional distance of any point along the relevant axis. $H_0$ allows the user to select the amount of wafer bowing, which was $2.5\lambda$ in the figure above. Given that successive bright contours correspond to a height difference of $[(\lambda)/2]$, the interference pattern observed is modelled by the function

$$I(x,y) = \cos^2(2h(x,y)\pi)$$

Figure 6.10: Simulated Fringes with a Sail Shaped Wafer Deformation

The similarity of both images would support the bowing hypothesis, which leads to the following conclusions:

1. A uniform air-gap cannot be achieved using a thin, flexible silicon substrate by the mechanical means described in this section due to bowing of the silicon wafer.

2. A reflecting substrate of greater mechanical strength should be used in further experiments.

The implications of these seemingly simple statements should not be thought of as trivial, and shall be returned to in section 6.4.2 where more serious consequences will be discussed. As a replacement to the silvered silicon wafer, it was found that silvered holographic plate ($\approx 1\text{mm}$ thick) performed very well as a less flexible substrate and was used in all further experiments.

2.2 Suitability of Spacer Material

A further investigation into the suitability of the polyester sheeting used as a spacer layer is also required. The fundamental assumption made in previous SLM fabrication is that

1. The spacer material chosen does perform its purpose adequately, namely it does not compress significantly and has both the specified thickness and uniformity of thickness to act as a spacer layer.

Although it is felt that this statement probably is true, a component playing so vital a role should undergo some form of scientific testing. This is particularly so when the difficulty of cutting spacers of the right shape and size has caused some to seek alternative ways of providing the required spacing. A technique whereby the suitability of the polyester spacer may be checked is that of vacuum packing, the origin of which (within this Group) is now briefly presented.

Vacuum Packing
At the time of these experiments, another research student within the Applied Optics Group, Steven Heddle, had found some success with liquid crystal cell manufacture using a technique known as \textit{vacuum packing}. Working in collaboration with the Group technician Mr. Garrie, Heddle placed two glass microscope slides, with the appropriate spacers, in a transparent polythene bag. Adhesive was placed around the edge of the slides and by means of a small vacuum pump attached to a thin tube placed in the bag, the air was sucked out. It was hoped that the atmospheric pressure would provide a uniform force over the surface of each glass slide and lead to a uniform gap thickness between them. It was felt that vacuum packing would be the most promising step forward towards the goal of cell thickness uniformity, as well as being most suitable for the investigations of this chapter as shall be seen.

**Experimental Arrangement**

In order that the thickness and compressibility of the polyester material be checked, a single rectangle of the spacer material was cut and placed along just one edge of the glass cube. A small polythene bag was used as an evacuation bag, commonly the type used to package components. These bags did not tear under the vacuum packing, but being made from rather thick polythene tended to obscure the fringe pattern from the cells. In fact, the combined effect of bag thickness with the fringes from the bag alone made observation of the fringes impossible whilst under evacuation. To counter this, araldite epoxy resin was carefully applied around the interface between the cube and substrate to hold the cell in the position it adopts under evacuation. The test cell was held in the perspex rig which was then placed into the evacuation bag and, once the vacuum pump was switched on, left for two hours in order that the araldite harden.

Figure 6.11 shows the resulting interference pattern photographed through the microscope. It is observed that a set of equally spaced, parallel interference fringes are obtained in accordance with the expectation of a linear variation in cell thickness. Unfortunately, the beamsplitter used was rather old but the only one available, and results in the non-fringe artifacts observed.

![Figure 6.11: Linear Wedge, One Polyester Spacer](image)

A total of 42 fringes are clearly visible over the main area of the cube, excluding the area over the spacers, which translates to a difference in height of $21\lambda$. As He-Ne illumination is used, this figure is found to measure $\approx 13.3\mu m$ whereas a difference in height of exactly $12\mu m$ would give rise to $\approx 38$ fringes. Care must be taken in the interpretation of this result, for the width of the spacer material may give rise to an increase in height as figure 6.12 suggests.

![Figure 6.12: Effect of Spacer Width on Fringe Count](image)
`Crinkling' of the material is not thought likely to explain the apparent extra thickness of the spacer due to the pressure bearing down on the cube. Given the nature of this experiment, it is fair to conclude that

1. Polyester sheeting does not significantly compress under vacuum packing and

2. The thickness of the material is nominally 12\( \mu \)m.

Neither conclusion is particularly unexpected though it was felt necessary to conduct the experiment as a matter of completeness.

Two Spacer Bars

The logical extension to the last experiment is to use two spacer bars at either end if the glass cube and repeat the whole procedure described above. As figure 6.13 shows, no fringes whatsoever are observed over any part of the cube, showing the air gap to be uniform to less than \([\lambda/2]\). Visual observations were made most carefully both using a CCD camera mounted so as to look down the microscope and with the naked eye. At no time were any fringes observed, and any structure perceived in figure 6.13 has been verified to belong to the beamsplitter.

These experiments led to confidence both in the integrity of the polyester spacer material and the process of vacuum packing as a means of producing a highly uniform air-gap, at least in the test cell structures used here. It was thus decided to continue test cell experiments with the two spacer / vacuum packing technique in the search for alternative affixation techniques.

![Figure 6.13: Vacuum Packed Cell - Two Polyester Spacers.](image)

2.3 Alternative Adhesives

Given the messiness of araldite epoxy resin, the time required to harden etc. it was natural to investigate other adhesives for use in SLM assembly. Superglue, though extremely strong in general, was ruled out out due to its poor bonding with glass and low viscosity (difficulty in applying accurately). Of particular interest was an ultraviolet curing glue, which achieved a very strong bond in a matter of minutes after exposure to a UV light source. The UV-cure glue has very little viscosity and may be applied in minute quantities with a syringe. By comparison, araldite is extremely viscous and becomes increasingly so as it hardens. Although it can be applied through a syringe, undesirable `threads' of glue cling to the syringe tip as it is pulled away from the site of application.

To study the UV-cure glue further, the interface between the reflecting substrate and glass cube was lightly coated around the edges with UV-cure glue from a syringe. Evacuation takes place and once all air has been expelled from the bag, the UV light source shone through the perspex onto the cell. After five minutes, the cells were placed in the interference bench for examination. Several test cells were made in this way, with varying amounts of glue used. Figure 6.14 shows one such failed cell.
It was found that no matter how small the amount of glue used, there was no way to avoid some seepage into the air-gap layer. Both UV-cure and araldite are compared in table 6.1.

<table>
<thead>
<tr>
<th>UV-cure</th>
<th>araldite</th>
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</thead>
<tbody>
<tr>
<td>Very strong bond</td>
<td>Very strong bond.</td>
</tr>
<tr>
<td>Low viscosity, gets everywhere</td>
<td>Highly viscous, stays where placed.</td>
</tr>
<tr>
<td>Infinite lifetime before hardening</td>
<td>Workable lifetime of minutes</td>
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<tr>
<td>Full bonding strength 5 mins from cure</td>
<td>Full strength after several hours</td>
</tr>
</tbody>
</table>

Table 1: Comparison of Adhesive Properties

Summary

The results obtained from the experiments carried out using small test cells demonstrate the suitability of both the polyester spacer material and characterise two adhesives for possible use in an improved SLM fabrication technique. Further, the technique of vacuum packing has been shown to be highly effective in the formation of a uniform air-gap, the desirability of which has already been discussed.

The success of vacuum packing relies upon a uniform pressure over the surface of the glass block. If, however, the evacuation bag collapses in such a way that the material of the bag is unevenly stretched this will result in an additional force on the cube in a direction possibly at an angle to the cube normal. This force may, if large enough, cause the air-gap layer to take on a wedge shape. Although this was not observed to occur with the test cells processed in this manner in this chapter, this was in all probability a matter of luck. However, several types of evacuation bag were tested - clingfilm, double thick bags, etc. - and only the single thickness bag found to stretch just enough to completely surround the perspex rig without either ripping or being just too thick to collapse uniformly. It shall be shown in section 6.4 that even a partially successful vacuum packing may still be useful.

3 A New SLM Assembly Technique

In this section a detailed account is given of an SLM assembled using techniques which have their basis in the test cell results of section 6.2 and which it is proposed offer a significant improvement over earlier fabrication procedures. The new assembly technique offers both a device of superior cosmetic quality and, it is hypothesised, longer lifetime. Vacuum packing is employed for the first time in this Group in the fabrication of a packaged chip SLM.

Firstly, a brief description of an improvement in cleanliness of assembly environment is given, an improvement to which this author can lay no claim other than a fair share of the taping of the windows and vigorous dusting/mopping/polishing undertaken in preparation of the room.

3.1 Environmental Cleanliness
The construction of a `clean' room within the Applied Optics Group late in 1990 provides what is hoped to be a significant improvement in reduction of atmospheric particulate contamination. The air in the room is recirculated through large filter banks, also passing through a condenser system to remove as much water vapour as possible. Although no figures are available for the particle count, the filters do remove a significant amount of dirt from the air as judged from their very dirty appearance on periodic changing. Entrants are required to wear disposable paper hooded suits and cover boots, as well as surgical masks and gloves to reduce the spread of particulate material into the clean room. Entrance is via an antechamber over two 'tacky-mats' which further remove dust from footwear, and the pressure in the main clean room is slightly greater than atmospheric as an extra precaution against contamination. All SLM assembly performed in this project was performed in this clean environment, which it is hoped will reduce liquid crystal alignment errors by particulate contamination to a minimum.

3.2 Preparation of Components

The two basic components of a Spatial Light Modulator, namely the packaged microchip and the cover glass cube, remain unchanged and their initial preparation is here described.

1. Glass Cube Formation
   The glass cube is cut by diamond saw from an Ealing Utility Grade optical flat, thickness 6mm and measuring 5x5mm on the face adjacent to the VLSI backplane, just as used in the test cells of the previous section. The cubes are then cleaned by washing in heated chromic acid for two hours.

2. Cube Coatings
   An indium-tin oxide layer of approximately 700Å thickness is sputtered onto each cube to act as a transparent counter electrode. Several cubes are processed at once, and after this initial preparation are sealed in an airtight container and transported to the Clean Room.

3. Ion Bombardment
   Both the packaged chip and several cover glass cubes are placed in an evacuation chamber which is pumped down to 10^{-5} torr. A high tension electric field within the chamber causes ionisation of the remaining molecules within the chamber by an acceleration/collision process. The high velocity ions bombard the exposed faces of the glass cubes and chip and, in theory, remove impurities at a molecular level adhering to the surfaces in question. A green glow is observed (presumably due to oxygen recombinations) in this process known as ion bombardment.

4. Aluminium Contact
   The chips are removed from the chamber and the cubes placed in a holder which exposes only a thin strip (≈1mm) of the lower face and one side face. An aluminium contact is sputtered onto these regions forming a layer ≈1000Å thick.

5. Alignment Layer
   The chamber is returned to atmospheric pressure and a small amount of silicon placed in a heated `boat' beneath the chip and cover cubes. Both the chip and cubes lie at an angle at an angle of 60° to the horizontal, the angle shown in figure 6.3, so that a microgroove structure forms on each surface and acts as an alignment layer for the liquid crystal molecules. Sputtering continues until the film thickness reaches ≈250Å, a figure which Heddle [64] has reported significantly reduces the formation of local domains within nematic BDH E7 liquid crystal as used in this project.

The components are now ready to be assembled into a complete spatial light modulator. Note the main improvements in preparation are the provision of a very much cleaner working environment and the ion bombardment of the components. Further, the alignment layer material has been changed from magnesium fluoride to silicon oxide in routine experimentation by Mr. Garrie and has been shown to possess good alignment properties [65]. Research within the Group [64] shows to cause fewer local alignment errors (domains) if the alignment layer is deposited to a thickness of 250Å. Consequently one would hope to obtain, upon assembly, a device exhibiting both uniformity of reflection over each mirror and high contrast between the ON and OFF
states due to the care taken in the preparation of the surfaces in contact with the liquid crystal.

3.3 Assembly

Assembly of the SLM is conducted in the Clean room, the stages once again are itemised for clarity. A comparison of the previous technique with that of Ranshaw is given at the end of this section.

1. The chip in its ceramic carrier is mounted onto a specially constructed assembly jig and clamped into position. This jig, designed and constructed entirely by Mr. Garrie, incorporates a platform which has both translational and rotational degrees of freedom. It is to this platform which the ceramic chip carrier is attached. See Figure 6.15.

![Figure 6.15: SLM Assembly Jig](image)

2. Two spacer bars are cut with a surgical scalpel from 12\(\mu\)m thick polyester sheeting, each having dimensions of approximately 4mm\(\times\)0.5mm. The spacers are picked up by the scalpel to which they are attracted electrostatically and carefully laid on either side of the glass cube. Damage at this stage easily occurs due to the strong attraction of the spacers to anything they come into contact with. Figure 6.16 shows the location of the spacers relative to the aluminium counter electrode, a consideration of importance when the cell comes to be filled.

![Figure 6.16: Spacer Location on Cube](image)

3. A small nozzle connected to a vacuum pump, shown in the figure, acts as a vacuum chuck with which to hold the glass cube above the surface of the chip. The nozzle diameter is approximately \(\frac{2}{3}\) that of the cube allowing relatively easy placement, though the cube edge may not lie parallel to the microchip edge at this stage. Rotational misalignment is countered by the micrometer controlled rotation of the chip platform. When placing the cube in the vacuum chuck care must be taken to ensure the aluminium edge lies parallel.
to the short side of the underlying ceramic carrier so ensuring a parallel configuration of the alignment layers on chip and cube.

4. The ceramic carrier is moved under the glass cube and the cube lowered quickly at first by micrometer screw until it is within about 1mm of the chip surface. Final rotation and translation of the cube is performed with the aid of a binocular microscope, and the cube is lowered very gently down until it just touches the chip surface. Approximately half a millimeter of play is found between the cube sides and the bonding wires of the chip, very little even using the microscope.

At this point the knowledge and experience gained from the test cell experiments is drawn upon, specifically that of vacuum packing. It has been shown that the spacers in question provide a uniform air-gap if both substrate and cover cube are optically flat and vacuum packing is employed. Two questions arise in consideration of the practical implementation of this technique to the situation here. Firstly, will the evacuation bag used collapse into the space between the glass cube and ceramic carrier and thus break the fragile bonding wires? Secondly, how will the technique perform when the substrate upon which the spacers lie is actually highly non-flat, the spacers lying over areas of pixel circuitry estimated to lie several microns [66] above the mirrors.

Both questions can only be answered by experiment and to this end the description of the remaining stages of fabrication is now continued with.

1. Vacuum packing is to be employed. In order that the cube does not move during the process, it must be fixed lightly into position initially and then set solidly once under evacuation for several hours. Two rectangular glass support bars, of dimension 10mm×4mm, are cut from microscope slides. One at a time, the bars are laid on the ceramic carrier and edged gently along until the short end just touches the glass cube still held in the vacuum chuck.

2. UV-cure glue is applied by syringe along the three edges of the glass support bar not in contact with the cover cube, and hardened immediately with the UV light source visible in figure 6.16. This saves time and results in a very clean, strong, localised area of bonding. It is of no consequence that the glue runs somewhat underneath the glass before curing, which occurs after five minutes of UV illumination.

3. In order that the glass cube be held accurately in position until transportation to the evacuation bag, two small spots of araldite Rapid epoxy resin are applied at the place where each glass support bar touches the cover cube, as shown in figure 6.17.

![Figure 6.17: Size and Position of Araldite Spots](image)

Each spot is applied through a large bore syringe, and remains tacky for approximately five to ten minutes. The assembly is left for two minutes to allow the araldite to become tacky enough to hold the cube in position and the vacuum chuck switched off.
4. Slowly the vacuum chuck is raised clear of the chip and the complete device removed from the assembly rig and placed on top of a specially shaped aluminium block which will support the chip during evacuation so the delicate package pins are not crushed. This is then placed into an evacuation bag. In order to obtain as uniform a bag collapse as possible, an angled copper tube drilled along its length was placed inside the bag, as shown in figure 6.18. To the other end of the tube the vacuum pump was connected through a valve. The pump is started and the valve very slowly opened, allowing a slow, controllable collapse of the polythene bag. The glass cube is pressed flush against the surface of the chip, movement being allowed by the still tacky araldite.

![Copper Tube used in Evacuation Bag](image)

Figure 6.18: Copper Tube used in Evacuation Bag

5. After two hours, the pump is switched off and the SLM removed from the bag and aluminium block. At this stage, the air-gap may be inspected with the interference arrangement if so desired and more shall be said of such observations later.

6. The SLM is placed on a temperature controlled hotplate in an evacuation chamber and the air evacuated. By heating the device to approximately 100°C it is hoped that any contaminants present on the surface of the chip and lower cube face will be 'boiled' off. This process is known as de-gassing and is aimed in particular at removing water vapour from the surfaces which is harmful to the liquid crystal. Although the measured temperature of the hotplate at any given time is liable to be higher than that of the SLM, it is expected that conduction to the SLM will raise its temperature to be approximately that of the hotplate or slightly less within ten minutes or so. Figure 6.19 shows two SLMs, one constructed by the author and another by Ian Chisholm, as they emerge from the evacuation chamber. (The SLM nearer the camera has been constructed as described here but is fitted with a post-assembly fringe compensation rig to be described in the next section).
7. The (hot) SLM is removed from the chamber and filled with liquid crystal from a syringe placed along either of the two accessible sides of the chip. The spacers lie under those sides covered by the glass support bars and as such do not form a barrier to the filling of the cell. Filling takes place via capillary action so it is required only to place a drop of liquid crystal at the cube-chip interface to fill the cell. Liquid crystal placed in the cell whilst still hot has a reduced viscosity and thus fills easily, but more than this it is known that heating a filled liquid crystal cell improves the molecular alignment. At a certain temperature, liquid crystal approaches a change in state - the clearing temperature - where no order exists between the molecules. Upon cooling within a cell having a proper surface treatment (alignment layers) the molecules are found the align themselves much more easily with the microgrooves of the surface. This temperature is 68°C for the LC used in this project, so that de-gassing and filling whilst hot are complementary procedures.

It was found that the polythene evacuation bag did not collapse so much that it damaged the bonding wires, the glass support bars limit the extent of the collapse and thus also function as bonding wire protectors. Optical quality of the SLM assembles in this manner is discussed in the next subsection.

3.4 Optical properties of New SLM

The assembled SLM is shown in figure 6.20, which for purposes of identification is labeled SLM#2. Cosmetic quality has undoubtedly improved significantly, but the optical quality is of far greater importance. Test patterns shown in figure 6.21 were obtained showing excellent contrast between the binary amplitude states, with all 256 pixels functioning correctly.
Some electrical problems were experienced and were traced to poor electrical connections between the chip carrier and the interface. Although of a minor nature, correct optical alignment of the SLM is made difficult by the need to move the device slightly to achieve full electrical connection. Therefore, moving SLM#2 from its interface once it was working was not considered a sound proposition. Experimental work on optical correlation began almost immediately the device was found to function - which was several weeks after it was fabricated.

Fringes were observed over the chip, but it cannot be ruled out that these were not an artifact of the beamsplitter used in the optical bench. Beamsplitter fringes are sometimes observed to be eliminated in amplitude mode operation of the device, and certainly the test patterns of figure 6.21 show no signs of degradation of optical quality arising from cell wedging. This is in part due to the self-compensating phase delay properties of nematic liquid crystal used in FIB mode, as previously explained.

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In order that the fringe effects be better studied several more SLMs were fabricated in an identical manner and experimental results obtained merit a section unto themselves. In brief conclusion however, a successfully operating 16×16 SLM utilising the Field Induced Birefringence effect was fabricated for use in an optical correlation experiment, thus fulfilling the objective of this chapter's research.

4 Fringe Elimination

In order that fringes be eliminated from the SLMs constructed according to the method of this thesis, two post-assembly adjustment rigs were designed and their implementation is described in this section. The combined effects of circuitry and non-uniform evacuation bag collapse (leading to stress in the bag material and a component of force at an angle to the chip normal during evacuation) are suspected of causing fringes during vacuum packing of the SLMs. In the assembly process it is noted that no adhesive comes into contact with the chip surface. As such, the possibility exists for post assembly adjustment of the cube by affixing a small device onto the front of the SLM which pulls or pushes the cube until it is completely parallel with the chip surface.

4.1 Perspex Adjustment Rig

Figure 6.22 shows fringe patterns of an unfilled SLM, SLM#3, constructed according to the new procedures detailed earlier in this chapter. It is observed that a height difference of approximately 4λ exists across the extent of the cube as judged from the 8 or so equally spaced (approximately) fringes visible. Non-straight fringes may be a result of wafer non-uniformity which may or may not have occurred during vacuum packing. The chips are glued to the ceramic carrier in a standard microfabrication environment and the type, uniformity of glue thickness and method of affixation of the chip are not known in any detail.
However, during the process a vacuum chuck is known to be used to hold the chip around all four edges whilst the glue dries. The combined effects on the thin silicon of the chip cannot be ruled out as causes of wafer bowing beyond the control of this author. A perspex adjustment rig was designed to fit over the glass cube as shown in figure 6.23, where the rig is also shown in place over the SLM.

A square hole, 5.1mm on a side, is cut in the top of a thin piece of perspex. This fits over the cover cube and is set to lie slightly lower than the top of the cube by turning each of the four screws at the corners of the perspex slab. The cube is then glued rigidly to the perspex with araldite epoxy resin around the edges, using a large bore syringe. If the cube is held strongly enough in position, yet with a small degree of flexibility inherent within the araldite, it might be pulled slightly by turning the four screws until absolutely parallel with the chip surface as judged from observation of the interference fringes of the air-gap.

Figure 6.24 shows the resulting fringe pattern taken through the microscope of the same SLM with the perspex rig so adjusted. Although the rig was not perfectly adjusted, the improvement is nonetheless quite dramatic. Unfortunately, the bond between the ceramic carrier and glass support bars using UV-curing glue was not as strong as expected and the glass was removed from the package altogether. This arose from overstressing the perspex by turning the screws too far, so that it acted as a coiled spring. The smooth surface of the ceramic carrier would be hard to form a strong bond with using any adhesive, and the design was flawed in that a lifting action worked against the adhering action of the glues used.
4.2 Brass Adjustment Rig

With the experience gained from SLM fabrication and the perspex adjustment rig, a further spatial light modulator was assembled and is referred to as SLM#4. After fabrication the device was examined on the interference bench and approximately six fringes were observed over the device, corresponding to $\approx 3\lambda$ which is remarkable given the admitted crudeness of the vacuum packing technique used.

A new adjustment rig made of brass was designed, the fundamental operation this time being to push the cube into position, and is shown in figure 6.25. Metal was chosen as the fabrication material as it would not flex by anywhere near as much as perspex does upon turning the adjustment screws. Thus, a slight turn of the adjustment screws is translated as an equally slight movement of the glass cube without the additional spring effect of perspex when it bends.

In order that the metal plate be pulled down, two smaller perspex bars are incorporated into the design to act as 'feet' which would be glued to the ceramic carrier. In the figure these 'feet' are visible, and paperclips act as spacers to leave the correct height between feet and main plate whilst the rig is affixed to the chip. The square hole has a bevelled edge on the top face so as to make the application of the araldite easier, and less likely to come into contact with the top face of the cover cube. The whole rig as is laid on top of the SLM and the feet are first glued with UV-Cure glue to the ceramic carrier. This minimises movement of the rig which could knock the glass cube and cause severe damage to the SLM. Once cured, araldite epoxy resin is syringed out over the UV-cure glue join so that the feet are secured by two very strong adhesives indeed. Each screw is held in a threaded hole in the perspex feet, and is secured from turning by the same procedure, the holes in the metal plate allowing free movement up and down of the screws, hence the paperclips to obtain the required height. Four small nuts on the threaded guide screws may be used to pull the metal plate (and cube) in a downwards direction.

Next, araldite is syringed into the space between the cube top and the metal plate, its viscosity holding it together so fill in the (rather larger than intended) gap. The SLM is shown seated in the interface in figure 6.26, where the connections to the BBC Master computer are clearly visible on the right of the picture. The long red wire is attached to the counter electrode at one end and a small bread board visible through the beamsplitter at the
other, which modifies the interface to allow the specific counter electrode signals required by the Field Induced Birefringence effect. The weight of the metal plate is supported entirely by the glass cube, so that as thin a plate as possible should be used, the cube being attached to the glass support bars by only two spots of araldite.

Optical Quality of Filled SLM

Figure 6.27 shows the interference pattern present during near optimum adjustment of the rig. The rig was later to be deliberately de-adjusted once filled to observe the effects on the liquid crystal layer, and so it was deemed unnecessary to pursue an absolutely ideal adjustment at this stage.

The SLM was removed to the Clean room and the procedure of de-gassing and filling with liquid crystal, described in section 6.3.3, was performed. Figure 6.19 of the same section shows the SLM in the evacuation chamber just before it was to be filled. After filling, figure 6.28 shows the interference pattern observed. Note that transportation of the device entails touching the brass adjustment rig and a change (usually for the worse) of the interference pattern.
An `ALL PIXELS ON' test pattern, in amplitude mode, was displayed on the device, with a further slight adjustment to decrease the fringes, and is shown in figure 6.29. Note that the fringes are not always visible due to the configuration of the polarisers in the optical processing bench which doubles as an interference bench also. Two data lines (columns) are observed not to function and one enable line (row) also fails to operate correctly, which further interface testing with a logic analyser shows are all attributable to chip/carrier faults. Further, the cover glass has been slightly misplaced during assembly so that the aluminium edge covers two rows at the top of the device. This happens to be fortuitous in that the enable line has been shown to pulse whenever any of the other 15 enable lines also pulses. By setting the data lines for the 15th (uppermost) row to contain the row pattern of enable line 10 (lowest line is enable line zero) the data for row 15 (obscured) is loaded into the flip-flops of row 10, so that this row can now be used as well.

The bench polarisers were then rotated until the fringe pattern became visible and the four adjustment nuts turned slightly until one fringe filled most of the area of the chip. Upon polariser reconfiguration to amplitude mode, figure 6.30 shows the resulting image quality of an optimally adjusted rig and the effect on the same test pattern when the rig is deliberately maladjusted for comparison.

The improvement in optical quality compared to a badly fringed device (in this case deliberately made so) is highly significant. Unlike the perspex prototype, the metal adjustment rig has caused no damage to the SLM and, as the photographs of this section have shown, has greatly improved the performance of an SLM operating as an amplitude filter. As the patterns are only visible due to the essential phase modulation mechanism of the liquid crystal, it is concluded the performance as a phase filter should also be improved.
Anomalous SLM Behaviour

The last figure in particular shows that non-uniformities in the thickness of the liquid crystal layer can overcome even the self-compensating optical path length effect of nematic LC. Post-assembly adjustment rigs can be used to save a badly fringed device from the scrap heap, but the adjustments required are difficult to perform and are speculated to be of use only for the rather `forgiving' nematic liquid crystal.

Several SLMs constructed within the Group (Garrie) have been observed to operate successfully and with excellent contrast though significant fringing is apparent over the device. Indeed, figure 6.21 of section 6.3.4 shows fringing present on the device used in the optical correlation experiment of the next chapter, SLM#2 with no apparent harm to the pattern displayed. The spacing of the fringes, being a measure of cell non-uniformity, is however close to that which so damages the optical quality of SLM#4 in the deliberate misadjustment of figure 6.30. The question then is

`Why is it that, given an identical assembly procedure, some SLMs function seemingly unaffected by the presence of moderate fringing whilst others are highly susceptible to even slight degree of fringing?'

This question cannot be answered by the author and it is suggested that future study into SLM fabrication should direct itself to finding the solution. It may be a simple matter, for instance it is known that the introduction of a beamsplitter into an optical system in particular causes problems with coherent interference of multiple reflections.

Alternative Fabrication Proposal

As a conclusion to this chapter, a brief study of yet another fabrication method (not that of the author) is analysed with respect to post-assembly fringe correction. It has been proposed within the Group to fabricate SLMs using thin (≤ 1mm thick) glass which is glued directly onto the silicon wafer using a glue-writing operation, where the glue is carefully laid down in a thin layer all around the active area of the chip. The glue is to contain spacer spheres and vacuum packing is then to follow. This technique has been proposed (and indeed the glue writing machinery is being manufactured) as a means of fabricating SLMs of commercial quality having a very much larger number of pixels than the 256 pixel device of this project. This proposal is briefly analysed here in order that the difficulties involved be discussed with reference to the knowledge obtained in this chapter.

1. Optically flat glass becomes enormously more difficult (and therefore expensive) to produce as the thickness required is reduced. This is a valid, if somewhat commercial, objection to using thin glass.

2. Thin glass is much less rigid than the 5×5×6mm cubes used in this project, and is therefore highly likely to bow. Test cell results of silicon wafers of approximately the same thickness as that of the proposed glass show bowing is a serious problem in thin materials. As ferroelectric liquid crystal is intended to be used, bowing of the glass which may occur during affixation to the chip would have serious consequences. It is
suggested that a uniform layer of spacer spheres should cover the active area of the chip to minimise this effect rather than a combined glue and spacer combination.

3. Vacuum packing produces an air gap of high parallelism \((\cong 4\text{–}6\lambda)\), see later) but has been found to be insufficient as a one stage process to obtain flatness to anywhere near one wavelength of light. Therefore, post fabrication adjustment may be required to achieve such a stringent level of parallelism. By using a thick cube of glass which is not bonded directly to the chip, this section has demonstrated successful operation of one such adjustment device which minutely moves the glass cube. The thin glass proposed may cause difficulties as pressure on one edge, for instance, would result in a local deformation rather than movement of the glass as a whole. This is especially so if the glass is bonded directly to the chip where the chip surface itself may become deformed. However, it should not be ruled out that a very thorough investigation into vacuum packing (evacuation bag material & properties, evacuation pressure, rigidity of hardened glue etc.) would produce a higher standard of result than obtained by this author.

5 Summary

A Spatial Light Modulator of high optical quality has been fabricated for use in an optical correlation experiment. Traditional fabrication techniques have been reviewed and built upon to introduce new methods which should result in devices of consistently high optical quality. In particular,

1. In the new method, SLM fabrication takes place in a `clean' environment, reducing airborne contamination of treated surfaces. This is expected to provide a very much cleaner assembled environment that the laminar flow cabinet used previously.

2. Ion bombardment of components is a further new precaution to ensure the cleanliness of the surfaces to be placed in contact with the liquid crystal.

3. De-gassing of the SLM air-gap before filling has been introduced as a measure to remove atmospheric \(\text{H}_2\text{O}\) from the surfaces in contact with the LC, this being detrimental to the lifetime of the liquid crystal.

4. A technique known as vacuum packing has enabled the integrity of the polyester spacer material to be verified and has been shown to consistently produce an air gap flat to \(\cong 6\lambda\) when used in SLM construction. Further, a study of all previously manufactures SLMs within the Group has shown that 90\% have leaked their liquid crystal layer out of the device. An SLM assembled according to the traditional assembly procedure and assembled one month prior to the vacuum packed device SLM#2 has also leaked the LC after one year. The vacuum packed device has shown no signs of leakage to date, suggesting that vacuum packing lengthens device lifetime by providing a thinner LC layer which, due to viscosity effects, is more resistant to leakage.

Figure 6.31: SLMs both old and new.

5. Test cell simulations have enabled the introduction of new adhesives into appropriate stages of SLM
fabrication, and shown the merit of vacuum packing.

6. SLMs fabricated to the new assembly procedure are cosmetically much improved over the previous method of assembly. If fringing is observed to be detrimental to the operation of the device, the new design by its nature allows post-assembly adjustment of the glass cube to minimise these effects. Two such adjustment devices have been evaluated and one found to operate with a high degree of success.

7. Experimental results on both wafer bowing and post-assembly adjustment device operation point to the continued use of thick glass in fabrication of SLMs of the type used in this project.

Future areas of research should, it is suggested, seek to clarify the anomalous SLM behaviour in the presence of seemingly strong fringing. Also, the shape of the spacer may prove to be influential on the success of the vacuum packing technique. Two rectangular spacers were used in the new assembly method whereas previously a U-shaped spacer was cut, which may offer improvement but is very much harder to fabricate. The first SLM fabricated in this chapter, SLM#2, is further discussed in the next chapter on optical correlation, which was the 'raison d'etre' of this chapter. The quality of optical correlations with the limited space-bandwidth product of this SLM further testifying to the optical quality of the device resulting from the assembly procedures of this chapter.

Footnotes:


2. Heddle [64] has successfully used a solution of 9μm diameter glass rods suspended in iso-propyl alcohol, (1mg of rods per gramme of IPA) a technique originally tried in this Group by the writer of this thesis but rejected in favour of the polyester sheeting.

3. PhD student, working on the 50×50 pixel SLM designed within the Applied Optics Group by McKnight [61].

4. SLM was a practice SLM assembled according to the old procedures and is not discussed further.

5. This subject is currently receiving attention within the group with reference to the fabrication of large, commercial quality SLMs.

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