

Department of Electrical
and
Computer Systems Engineering

Technical Report
MECSE-20-2006

INTEGRATED PHOTONICS: PART II - Fabrication Processes for
LiNbO₃ Ultra-Broadband Integrated Optical Modulators

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INTEGRATED PHOTONICS: PART II – FABRICATION PROCESSES OF ULTRA-BROADBAND INTEGRATED OPTICAL MODULATORS

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Summary

Mach Zehnder interferometric modulators (MZIM) currently attract much attention in the modulation of lightwaves of different modulation formats such as RZ, NRZ, CS-RZ phase, amplitude or frequency schemes. This report thus presents the design and fabrication of the travelling wave electrodes and optical waveguide structures for ultra-broadband operations. A program for the design of the travelling wave electrodes of coplanar waveguide, coplanar structures and asymmetric co-planar structures are described with the procedures for the execution of the design package.

The fabrication processes for optical waveguides using titanium diffusion and the gold plated electrodes are described in details. The test results of the MZIMs and travelling wave electrodes are illustrated to demonstrate that we have implemented our design package and the fabrication of 30 GHz 3 dB bandwidth MZIM.

We further propose the extension of the operational bandwidth of optical modulators into the 100 GHz with ultra-thick metal layer of several hundreds of micrometers using the deep X-ray lithography fabrication processes.

Key words: Optical modulation, optical devices, integrated photonics, optical communications, Finite difference method, conformal mapping, fabrication processes, deep X-ray lithography, micro-technology, AUTOCAD.

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1. INTRODUCTION

Integrated photonics has evolved over the last thirty years from the proposal of optical waveguides in 1966¹ and then to guided wave optics and integrated optics in 1969² to the present generation of photonics, the integrated photonics. Concurrently optical fibre communications have progressed tremendously from a mere 10 Mb/s in 1974 to 40 Gb/s, 80 Gb/s and then 160 Gb/s per wavelength channels. The multiplexing of several wavelength channels has allowed the increase of the total transmission capacity over a single single mode fibre to few tens o THz over the S-C- and L- bands of the 1550 nm spectral windows. We also note that several modulation formats have also been generated³ by these external modulators.

The principal technique that allows the development of such enhancement of the transmission speed is the external modulation of Lightwaves, thus the minimisation of the broadening of linewidth of the laser sources. The external modulation is usually performed by photonic transmitters. Presently the most popular modulator is the lithium niobate (LN) interferometric types which are formed by an interferometric waveguide structures along which the Lightwaves interact with the electrical travelling waves via wideband travelling wave electrodes.

This report is the second part of a series of technical articles to present the fabrication techniques for Mach-Zehnder interferometric modulators (MZIM) in LN material system⁴. The processes for the design of the electrodes, optical waveguides using optical lithography are described including all chemical and packaging stages. We further extend this work with the proposal off X-ray lithography for fabrication of photonic transmitters that could operate into the mm-wave region (>100 GHz bandwidth).

¹ C. Kao and Hockham, "Dielectric waveguides" Proc. IEE, 1966.

² S.E. Miller, "Integrated Optics", BTJ 1969.

³ Readers are refered to several papers presented in the IEEE Worshop on Advanced Modulation Formats, San Francisco 2004.

⁴ LN Binh "Modelling of symmetric and asymmetric travelling wave electrodes for ultra-broadband optical modulation", ECSE Monash University, Technical report MECSE-8-2005

This report is organised as follows. In the next section we give the details of the design and execution of the design package of the travelling wave electrodes and the processes for fabrication of such electrode structures. Section 3 details the fabrication processes for optical waveguides, optical modulator structures and the integration of the electrodes and waveguide structures. We then propose the use of X-ray lithography for thick electroplating of the gold electrodes so as to produce optical modulators operating into the 100GHz region.

2. DESIGN AND FABRICATION PROCESSES

The design and fabrication of the interferometric modulators for broadband modulation and generation of advanced modulation formats require : (i) accurate and detailed design of the travelling wave electrodes, the guided optical waveguides, the interferometric guided wave structures, the electro-optic interaction and its effective overlap integral. (ii) Fabrication of the optical waveguides and the travelling wave electrodes; (iii) packaging of fibre-optical waveguide coupling ; and (iv) testing of optical and microwave properties of the MZIM. We show in the following the flow charts of the design and fabrication of these broadband optical modulators.

Figure 1 shows the flowchart of the design steps for the design of the travelling wave electrodes - all processes (step by step) for fabrication of the Mach-Zehnder optical interferometric modulator (MZIM). Four fundamental stages are:

- Stage 1: Numerical modelling and design of Mach-Zehnder waveguides and electrode structures using the finite difference and conformal methods – specification of modulator parameters including the design of the travelling wave electrodes and the design of optical waveguides and interferometric structures.
- Stage 2: Mask generation for electrode structures and interferometric optical waveguiding structures using AutoCAD
- Stage 3: Fabrication processes of a wideband optical modulator.
- Stage 4: Modulator packaging including fibre-diffused optical waveguide coupling, pig tailing and testing

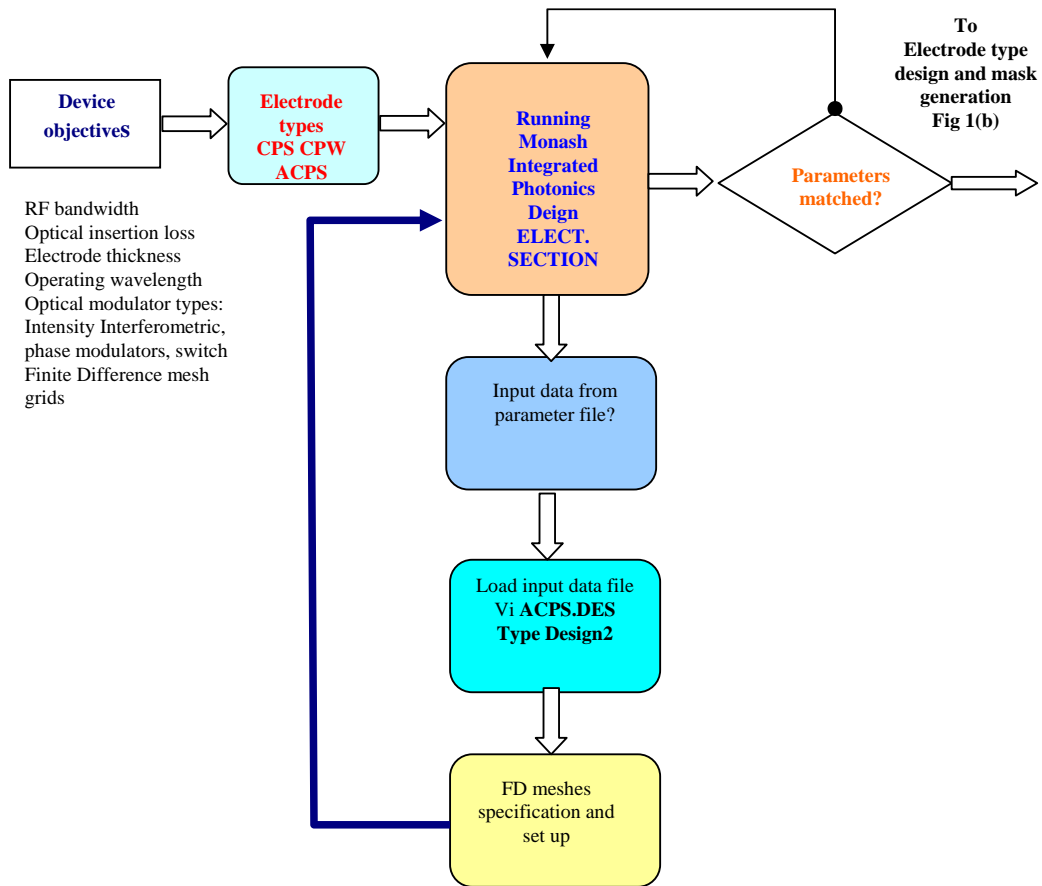


Figure 1 (a) Travelling wave electrode design for ultra-wideband interferometric modulation

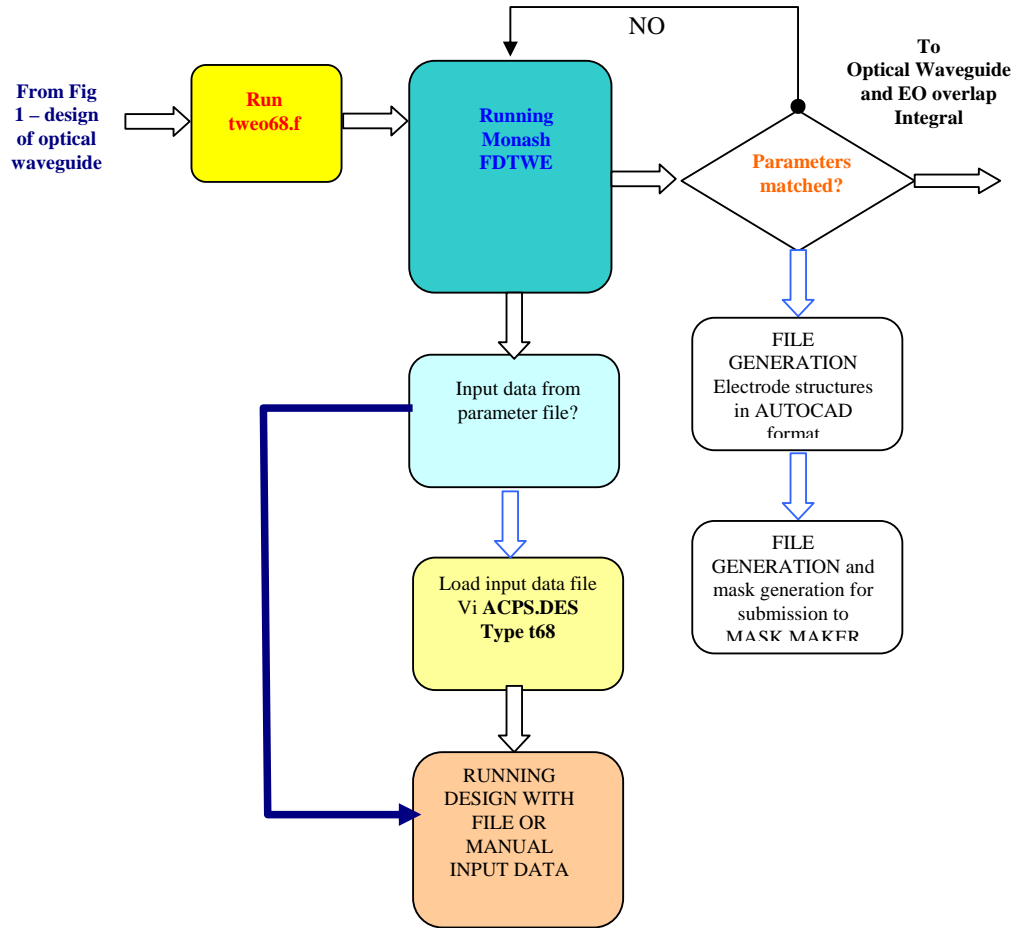


Figure 1 (b) Generation of AUTOCAD data file for mask generation

2.1 DESIGN SOFTWARE PACKAGES- FDATWEA

All programs using for the design of ultra-broadband integrated optical modulators have been developed for GHz optical modulation devices written by TW Chua ⁵ in which the Finite Difference Method (FDM) and Conformal Mapping have been extensively exploited to minimise the computing time and maximise the accuracy.

2.1.1 The design of travelling wave electrode structures

Figure 1(b) shows the flowchart of the steps of the design of the ultra-broadband travelling wave electrode types such the coplanar waveguide (CPW), the coplanar .and asymmetric coplanar structures (CPS and ACPS). The details for the steps and execution procedures for the program are shown in the next section.

2.1.2 Hardware requirement

The programs using for designing electrode devices are must be run in a Unix or PC system which can be **mdw, mda, and redyn or fawlty** machine⁶. Due to the size of the matrix that use to store result is large (500x500), a memory of 1 – 10 G RAM may be required to solve the sparse matrix of 10,000 x 10,000 elements. Naturally the lower memory capacity demands longer execution time. It is expected that the running time would be around 4-5 minutes of CPU for the design of a typical travelling wave electrode and MZIM structure.

The 2 main files of the design of a travelling wave electrode are: **design2.f and tweo68.f** as indicated in Figure 1

The external files linking by 2 main programs are:

- **Chargeo23.f, cpwo4.f, cpso3.f, conformal, acps09.f**
- **chargeo23.o, cpso23.o, tweo58.o, acps09.o, cpwo4.o** then linking to programs for generation of the executable files.

⁵ TW Chua “Numerical modelling for the design and analysis of high speed integrated optical modulators”, M Eng Sc, 1996, Monash University.

⁶ A number of this workstation may not be supported by Monash IT Computer Centre.

The names of all input data files are:

- **acps.des, cpw.des, and cps.des** (input data files for design2.f program)
- **acps.in, cpw.in, and cps.in** (input data files for tweo68.f).

The command for compiling all these FORTAN 77 packages is:

f77 -o filename filename.f (filename is name execution file)

The following commands are for compiling program applicable for the mda machine (Alpha machine):

mk f1 & (f1 file with extension is f (filename.f))

then **mk1 f1 f2 f3 . fe** (**f1-f3** are files with extension is **o** (filename.o) and **fe** is the name of the link file, using for execution). Then call **t68** for the execution file (fe = **t68**).

All the **NSPCG** files are the FORTRAN 77 math files, so there no need to compile them, but they must be included in a directory called **nspcg.o**.

2.2 Execution of simulation programs:

Two main programs are to be used for the design of the travelling wave electrodes:

- **design2.f**
- **tweo68.f**

The **design2.f** program generates *approximate* results for use as the initial guest data to ensure the convergence of the matrix solver. This gives the range of the electrode gap and the width of electrodes which would give the best approximation for bandwidth (BW), V_{π} , etc. The using these data outputs one can run the **tweo68.f program** to double check and obtain more accurate parameters which can then be checked with the specifications. The **tweo68.f** gives us very accurate results with about 5% differences compared to experimental results. Furthermore another two steps must be followed for designing different types of electrodes: the CPS and

ACPS. For ACPS the **acps.des** and **acps.in** are used as the input data files for the **design2.f** and **tweo68.f** programs.

2.2.1 Step 1: Running the **design.f** program:

This program prompts questions requesting all information required for calculations:
(i) Calculation mode (individual design or design curve); (ii) Structure type of electrodes: ACPS, CPW or CPS (iii) Name of files which the data output can be saved
(ii) The length of the electrode in cm (iv) The range of the operating frequencies (f1,f2) in GHz (v) The thickness of the electrode (ts) in μm (vi) The range of electrode width (w1,w2) and gap (g1,g2) in μm that may satisfy the requirement; (vii) The thickness of the buffer layer (SiO_2 -thin film) in μm .

These parameters can be loaded directly from an input data file or entered manually. To run program and input data from the file then type:

```
design2 < acps.des
```

The **design2.f** program imports all input data from the input (**acps.des**) file instead of reading data from the keyboard. Alternatively one can instruct the program reading data from the keyboard. In this case type

```
design2
```

The program will prompt all above questions. The output results are stored in two files. One contains all data about characteristic of the device and the other all the values of the scattering parameters S_{21} . The value of S_{21} allows us to evaluate the electrical insertion loss of the device.

All output data can be plotted out by using the **Gnuplot** or **Matlab** softwares.

Using **Gnuplot** software to plot all data you want to see. This software can plot many curves in one graph. To use gnuplot software, type:

```
gnuplot <enter> (run software)
```

User will now be in the **gnuplot**, and then plots of all results are stored in the output files. Gnuplot can be used to plot the results:

gnuplot> plot “filename” using xcol:ycol, ‘filename’ using xcol: ycol

(Where **xcol**, **ycol** are columns to plotted, and filename is the name of the result file to be plotted)

From the graph or the output data file, we could inspect all possible range of data that may satisfy requirement such as gap, width, thickness of gold layer, thickness of SiO₂ layer). Then use the **tweo68.f** program to determine the set that are closed or matched with the specified parameters.

2.2.2 Step 2: Running **tweo68.f** program

The running procedures for this program are the same as for **design2.f** program. The input data can be imported from the input file or from the keyboard. There input data files corresponding to three types of electrode are **acps.in**, **cps.in**, and **cpw.in**. AT the prompt the input data file requests the following dat: (i) Type of electrode structures :(ACPS, CPW, or CPS); (ii) Type of LiNbO₃ wafer (crystal orientation); (iii) Thickness of air region (μm) (choose 250 μm); (iv) Thickness of gold layer (μm); (v) Width of electrode (μm); (vi) Gap of electrode (μm); (vii) Thickness of buffer layer (μm); (viii) Thickness of LiNbO₃ substrate (mm); (ix) Number of grid points in x-dimension (xdim) and in y-dimension (ydim); (x) Bandwidth (GHz); (xi) Operating wavelength (μm); (xii) Type of results you want to get (1: compute everything, 2: Z and nm, 3: V_π and γ only); (xiii) Name of output data file

All the above data are stored in the file **acps.in**, **cpw.in** or **cps.in** which are input data files for running **tweo68.f** program.

To run **tweo68.f**, then type

t68 < acps.in (if you want the program gets data from the file and the electrode device is acps)

The program automatically imports as all data values from the input file, calculate and output results.

or **t68** (if users intend for the program importing data from keyboard/manual entries)

The program will prompt all questions asking for device's information. All results are stored in a file. To see result, type

vi filename

If all the result in this file satisfies device's requirement, then print out this file or record them for drawing and fabrication. If the results do not satisfy, use other values or adjust input data then run program again til results matched with the device's parameters.

2.3 METHOD OF DRAWING DEVICES

2.3.1 Flowchart for MASK drawing

There are many steps in drawing a MASK using AutoCAD software. Figure 3 summarises the steps for the use of AutoCAD for drawing a MASK. Details of all steps is described in part 3, using AutoCAD for drawing devices.

2.3.2 Design rules for ASM 2500:

The following rules only apply with the ASM 2500 software of the mask generator as specified by the Defence Science and Technology Organisation (DSTO). Note that this may be different with other mask manufacturer. AutoCAD software is a general purpose drafting program we can use for electronic mask layouts. However there is a limited of using AutoCAD. Some commands are strictly used in drawing (see DESIGN RULES FOR ASM 2500 for detail).

Some rules for drawing the MASK are:

1. The ASM 2500 works only with DXF files so a drawing mask file drawn in AutoCAD must be converted to DXF file and converted back to DWG file then reconverted back to DXF file for checking.
2. The drawing grid size unit can be **mm, μm , inch**. **But** often we used μm because of the dimension of our devices are in μm)
3. The area of the drawing mask is not higher than the maximum is 6'x9' but our mask area is 3'x3'.

4. Set Grid Snap mode and set it as small as possible depending on your requirements. Normally a snap size equal to 0.1 is used.
5. **Set Orth ON** whenever it is possible. A pattern generator is most efficient when imaging orthogonal rectangles.
6. **The LINES command:** the endpoint of a line must touch precisely and one line can not share by more than one closed boundary.
7. **The PLINE command:** the width of the poly-lines can be zero or finite. The poly-line has zero width must close (starting and end points must touch). The poly-line with finite width must not touch or cross upon itself.
8. **All blocks** must be completed before inserting into the master file.
9. **Islands:** this is used when you draw alignment marks or there is an island in a device. The AutoCAD's PLINE command with zero width is used for the best result (see DESIGN RULES for SAM 2500)
10. Any gap in a device **must be not less** than 2.5 μm

Before starting the drawing, the following values must be known or determined:

- The area of the each pattern (width and height)
- The area of the mask (master file) you are going to use (width and height)

These data will be used to set the drawing area.

2.3.3 Using AutoCAD:

2.3.3.1 Set up drawing window:

AutoCAD can accept command in lower case or capital letters. To run AutoCAD, log onto the drive or directory containing the AutoCAD program file and enter:

ACAD

Then the main menu appears on the display screen. It has 8 options and the main menu would be:

MAIN MENU

0. *Exit AutoCAD*
1. *Beginning a NEW drawing*
2. *Edit an EXISTING drawing*
3. *Plot a drawing*
4. *Print plot a drawing*
5. *Configure AutoCAD*
6. *File utilities*
7. *Compile shape/font description file*
8. *Convert old drawing file*

Enter selection:

If a new file is to be open for drawing then enter 1(new drawing), and if you want to open the existing drawing then enter 2 (an existing file). Then AutoCAD prompts:

Enter NAME of drawing: **<name of the file for saving> < enter >**

User is now in the AutoCAD windows and can start to draw. Because of our device's area is greater than the area of drawing windows, we must set up the drawing environment such as unit, drawing limits in the first instance. The following commands tell instruct users how to set up a drawing window. At the command area, do the following steps

command: LIMITS <enter>

ON/OFF/<Lower left corner> <0.0000,0.0000>: type 0,0 <enter>

Upper right corner <12.0000,9.0000>: x,y <enter>

(Where x and y are value of a point at the top right corner of the drawing window)

command: ZOOM <enter>

All/Center/Dynamic/Extents/Left/Previous/Windows/<Scale>: All <enter>

(Choose All for full window)

Now the dimension of the drawing window is equal (or larger) than the device's area.

To get the coordinate of a point, press **ctrl-d** (at the same time), then you will see two numbers on the top right corner of the window that indicates coordinate (row, column) of that point. If you move the mouse then the numbers are also change. To turn ORTH ON by pressing **ctrl-o** (at the same time)

command: GRID <enter>

Grid spacing(x) or ON/OFF/Snap/Aspect <10.000>: < size of grid lines> <enter>

command: SNAP <enter>

Snap spacing or ON/OFF/Snap/Aspect <1.0000>: < size of the snap lines> <enter>

The snap size is as small as possible, that makes the drawing more accuracy (I used 0.1 for size of snap lines).

After you set-up the drawing windows, now you can start to draw

Device drawing:

Our devices consist of two types:

- Machzehnder (MZ) Waveguides
- Electrodes

There is a special function for drawing the MZ waveguides, and the electrode structures can be drawn to match with waveguide structures by

Drawing Mach Zehnder Waveguides

Move the mouse to the top of window, the main menu will appear, then click special function. Users will see many types of waveguide pattern then choose Mach-Zehnder. After the selection, the following questions you will see at the command lines (one by one) and users must enter the values for each question:

Start point? (the point where you want to start)

Do you want to move the object yourself <Y/N>?:

Orientation ?

Length 1?

Length 2?

Length 3 ?

Length 4 ?

Radius ?

Angle 1 ?

Angle 2 ?

Width 1?

Width 2?

Note: The commands using in this special function are AutoCAD's PLINE with finite width value.

Meaning of all symbols in the special function can be found in the appendix 1. The gap between one waveguide to the other should be around greater than 20 μm to avoid interference between two waveguides.

* *Drawing Electrode structures*

- Two commands that users can use are: LINE or PLINE
- The PLINE command is very complicate. You must know beginning width and end width of a line.
- Using the LINE command is easier than the PLINE command if all alignment marks are out side area of the pattern. Try to place all alignment marks out side area of the pattern then your life is much easier. All the line must touch exactly (the end point of one line must be the beginning point of next line) and lines make a close figure.
- Drawing the alignment marks, the PLINE with zero width and right wind rule must be used (detail in the DESIGN RULES ASM 2500).
- Coordinator of a point can be entered by hand or by moving the mouse.
- After the drawing of all individual device components, then open a file (master file) to arrange all sub-structures including their superposition on each others to generate a drawing mask. This file will be sent to mask manufacturer to generate the mask.

To understand more about the design rules of ASM 2500 and AutoCAD commands, see DESIGN RULES FOR ASM 2500 and AutoCAD manual.

2.4 FABRICATION PROCESSES

2.4.1 The flowchart of fabrication procedures of a 20 GHz optical modulator:

The processes for fabrication an optical modulator are summarised in Figure 4, the flowchart of the fabrication of an optical modulator. Details of each stage are described in the following sections.

2.4.2 Fabrication procedures

Throughout all processes, LiNbO_3 substrates must be handled with the plastic (preferably teflon) tweezers to avoid damage to the substrates. All procedures are done in clean room at room temperature and yellow light, unless it is stated.

The plastics (or teflon) beakers or containers are used in all processes. Three types of photo-resist used are: AZ5214, AZ4210 and AZ4620.

Equipment: Spinner; A mask aligner (KARLSUSS MJB 3); A vacuum Oven; An ultrasonic cleaner; An electromagnetic hotplate stirrer; Magnetic rods; A 3-litre beaker (Glass); Microscope; An ultrasonic cleaner.

2.4.2.1 Process 1: Procedures for cleaning LiNbO_3 substrates

1. Using a cotton tip to clean a substrate with acetone (spray) in 1 minute
2. Rinse it with DI water
3. Clean it with Decon90 (using a cotton tip)
4. Rinse it with DI water
5. Dry a substrate by blowing nitrogen air
6. Check the substrate under microscope. If it cleans then bake it in a 90°C vacuum oven then store it in a FLUOROWARE container. Otherwise repeat step 3 to 6 if 2 there is dirt spots (brown colour) or repeat all steps if there is oil spots (multi colour)

2.4.2.2 Process 2: Ti thin-film evaporation

All clean substrates are placed on the metal plate (see picture in appendix 6 for how to place substrates on the plate). All data for Titanium evaporation process are attached in Appendix 5. For the best result of evaporation, all the substrates must be cleaned and baked (in the vacuum oven), and evaporated in the same day.

2.4.2.3 Process 3: Photo-resist layer coating

1. Turn on the SPINNER machine
2. Place the substrate on the substrate holder
3. Vacuum on
4. Blowing the substrate with N₂ air
5. Put photo-resist (PR) on
6. Adjust the time and speed meter as required
 - Time : 40 secs
 - Speed: 5000 rpm if using AZ4210 and get about 1.9 μm thick

5000 rpm if using AZ5214 and get about 1 μm thick

6000 rpm if using AZ4620 and get 6 μm thick

Detail of thickness of photo-resist had been measured and plotted

(see the graph for detail).

7. Press the operation button
8. Vacuum off
9. Take out the substrate
10. Turn off spinner
11. Place the substrate in the 90°C vacuum oven:
 - About 15 minutes if using AZ5214 or AZ4210
 - About 30 minutes if using AZ4620

12. Take the substrate out of oven and let it cool before going to next process.
The cooling time depends on thickness of the photo-resist layer, it is about 10 minutes/1 μm

2.4.2.4 Process 4: Photolithography

The KARLSUSS MJB 3 mask aligner is used for this process.

The machine **must be turned on in one hour** before the lithographic processing.

Exposure Time:

- AZ4620: 75 sec
- AZ4210: 45 sec
- AZ5214: 5 sec

Developer:

- AZ5214E and AZ4210: using 1 part of AZ400K mixed with 4 parts of DI water
- AZ4620: using 1 part of AZ400K mixed with 3 parts of DI water

The following steps are telling you how to use the mask aligner to get photo-resist pattern using for gold plating:

1. Place the mask on the mask holder of the mask aligner (device to be taken must stay in centre of the hole) then press vacuum button
2. Place substrate onto the metal plate then slidded it in.

(see operation manual for detail)
3. PR development
 - Place substrate on an island of the cleaner then vacuum on to hold the substrate

- Spray the developer into it (around) until PR removed
- Water it in about 1 or 2 minutes
- Dry a substrate with Nitrogen air (blowing)
- Bake it in the 90°C oven in 10 minutes before go to next process

Note: (i) Time to develop is about 50 secs (ii) The pattern must be checked carefully before doing further processes. If it is not as good as we expected then remove PR layer and repeat process 3 & 4.

2.4.2.5 Process 5: Titanium etching

Repeat process 3 and process 4 to get the photo-resist pattern of waveguides. The waste Ti surrounding the waveguides is removed by etching in a fast Ti etching solution consisting of 2 parts of HF and 98 parts of DI water (HF 2%).

1. Pour the Ti etching solution into the plastic beaker (small)
2. Place the substrate on the substrate holder
3. Deep it into the solution and wait until Ti starting to be dissolved
(normally it takes about 10 sec) , then immediately take the substrate out of the etchant and rinse a substrate with DI water in about 2 mins.
4. Dry substrate with N₂ air (blow)
5. Checking Ti waveguides, if all waveguides are good and if
 - The substrate is clean (especially the waveguide's area) then go to 6
 - The substrate is dirty then repeat process 1 (do it lightly) until substrate is clean then go to step 6, otherwise, remove the Ti layer
6. Bake it in an oven at 90°C in 15-30 minutes then the substrate must be stored in a clean FLUOROWARE container for diffusion.

2.4.2.6 Process 6: Titanium diffusion

Ti film diffuses into LiNbO₃ substrate in a diffusion furnace under high temperature. Only three substrates can be diffused at a time due to the small size of substrate holder boat. Conditions of diffusion are:

- Time : 7 hr
- Diffusion temp : 1050 °C
- Flow rate of O₂ : ~ 0.5 lit/mins
- Temp. of water : 25°C
- Wet atmosphere with dry oxygen air bubbling through 1/2 bottle of warm DI water (set temperature = 25°C)

(See the manual of the furnace for more detail of furnace operations).

Note: Place the substrates on boat (3 at a time), and only move the boat in when temperature of the furnace reaches 1050°C. Move them in and take out of the furnace very slowly (about 20 to 30 minutes). After the diffusion, all the waveguides must be examined under a microscope before polishing. If all waveguides are not good (not smooth) then do not polish.

2.4.2.7 Process 7: Polishing

There are about 3 main steps in this process and the first step of preparation is very important. If this step is doing well then the two edges of the substrate are very sharp therefore low coupling loss could be achieved.

Only one substrate can be polished at a time. Serval things users must prepare before polishing the substrate:

- Cut the LiNbO₃ substrate (21x11x1.0 μm) into small pieces (about 4x11x1.0 μm) Then clean them and store them in a container, those will be use for polishing process

- Clean the substrate holder and cut the **Post-it** paper (glue part) into small pieces (about 4x11 mm)

Step 1: *Preparation of the substrate*

1. Place a small piece of Post-it paper to the substrate holder
2. Place the substrate (back side) in contact with the paper
3. Place the small LiNbO₃ in contact with the substrate
4. Stick the small piece of post-it paper on the small piece of metal then place it back to the hold. Using a Philip key to draw gently two bolts in until you see the COLOUR RING between the substrate and the small piece of LiNbO₃
5. If you think they are not well in contact, then unpack and repack them again until you think it is good in contact (see the colour ring) for polishing.

Step 2: *Polishing*

1. Use the paper sand: the P.1200 or P.800 will be used in this step. Cut the sand paper into a small circle with a diameter is equal about 1/2 diameter of the polishing disk. Then placed it on the disk (however, the size of sand paper is up to you).
2. Turn on the machine. Hold the substrate holder by hand to polish until the unwanted edge of 2 LiNbO₃ are removed
3. Turn off the machine and clean them with acetone (using cotton tips). Observe it under microscope, if the gap between the substrate and the small piece of LiNbO₃ is very small. Then clean it with Decon90 by using ultrasonic cleaner in about 15 mins, and then go to 4 if it is very clean. Otherwise, repeat 1-3
4. Using diamond paste

a. Using the 9 μm polishing disk:

- Place the 9 μm disk into the machine
- Place the substrate holder onto the 9 μm then lower the arm of the machine for holding it, then turn machine on
- Drop 3 drops of Karosene onto surface of the polishing disk before running the machine. Running time is about 20 mins,
- Turn off the machine and wash the substrate holder as before then observe it under microscope. If the gap between the substrate and the small piece of LiNbO_3 is smaller, then clean them in 15 minute (using ultrasonic cleaner and Decon90). If it is not then repolish it again until the gap is smaller. If the edges are very clean after using ultrasonic cleaner then go to next step (step b), otherwise re-clean it.

b. Using 3 μm disk

Place the 3 μm into the polishing machine then repeat all things in

(a)

If two edges are good, then repeat step (a) with 1 μm disk and again with 1/4 μm disk. However, time to run the machine is about 8 minutes (about 12 minutes less when you used 9 μm and 3 μm disks).

Step 3: Inspection

If the edge is good (no chips, not broken ...) then you see the bright spots along the edge of the edge (they are end points of waveguides). If you do not see any bright spots then there are several things you must do are:

- Re-clean it, then observed it again, if you see them then go to step 4

Continue to polishing in about 5 minutes then recheck it, if you see the bright spots then go to step 4. If you still do not see any of bright spot, then unpack all and

repeat step 1 to step 3 until you see number of bright spots along the edge of the substrate.

Step 4: *Finish polishing of the other end*

Unpack all things out of the substrate holder. Clean the substrate then repeat the above step 1 to step 3 to polish other end of the substrate.

After the polishing of the two ends of waveguides, check the waveguides by applying the white light into one end of waveguides and you see the light is out at other ends with the aid of a microscope. The two end points of waveguides must not be chipped and it must be flat for low and minimum coupling loss. If the above features are not satisfied then unpack them (take the substrate out of the substrate holder for cleaning), then polish the other end (repeating step 1 to step 3).

This is a very time consuming process and it would take at least 1 1/2 days to finish polishing one substrate.

2.4.2.8 Process 8: Testing and determination of guided optical modes

All substrates after polishing must be subject to a test of optical insertion loss before going to further steps. All waveguides in the substrate must be numbered before starting to test.

Firstly use the 633 nm laser for alignment between the fibre and the waveguide, and then use the 1300 nm or 1550 nm laser for measurement of the optical coupling loss (insertion loss). The results must be taken are: (i) Input power from laser (P_{in}); (ii) Output power from one end of the testing waveguide (P_{out}); (iii) Calculate optical insertion loss (P_{loss}); (iv) the $P_{loss} = 10 \log (P_{out} / P_{in})$

Write down results for each waveguide then choose the one has less optical insertion loss. This waveguide will be used to place electrode on.

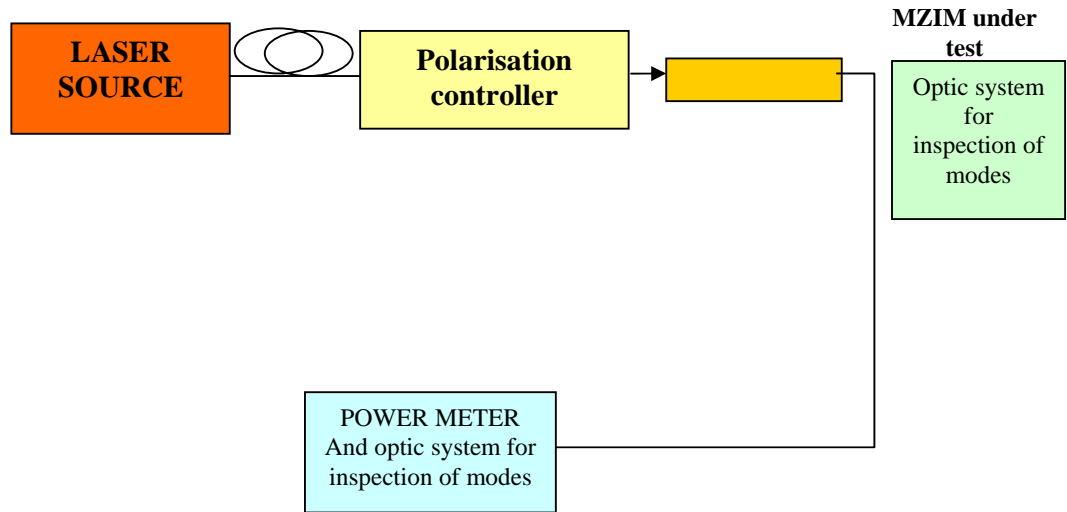


Figure 2: Schematic diagram of optical system for testing coupling loss of waveguides after polishing

2.4.2.9 Process 9 SiO₂, Chrome (Cr) and Gold (Au) evaporation

- The SiO₂ can be deposited on the substrate by the Balzer e-beam evaporation machine (not very good, bubble) or PCVD system (Plasma System). Thickness of the SiO₂ layer is varying from 0.6-2 μm, the thicker SiO₂ layer the higher V_π produce
- Thickness of Cr: 200 Å
- Thickness of Au: 1000 Å

Cr and Au layers are evaporated by the BALZER e-beam evaporation machine.

2.4.3 Preparation of electrode pattern (PR) using for Gold plating:

Repeat processes 3 and 4 to get the photoresist electrode pattern. PR AZ4620 and the reverse mask are used this time. The electrode pattern must be checked carefully to insure that there is no short circuit between the hot-line and the ground plant of an electrode. Also check under-etch of photoresist pattern, if the difference of the width of the photo-resist pattern and the width of the original pattern is about 2 μm then do

gold plating. If the pattern does not satisfy the above conditions, then use acetone to remove photo-resist layer and repeat processes 3 & 4.

Record the ratio between gap and width of the electrode after developing. Then bake it in the 90°C vacuum oven in about 20 minutes, take it out and let it cool in about 5 minutes before doing electroplating.

2.4.3.1 Process 10: Electroplating

Equipment: (i) 1 of 3-litre beaker (glass); (ii) 2 litres of Gold solution (iii) a magnetic hotplate stirrer (iv) a magnetic rod; (v) a digital multimeter (it can be measure $R > 1\text{ohm}$, $I > 4\text{mA}$, and $V > 1\text{V}$); (vi) 15V DC power supply

Procedures:

1. Making the plating bath: Pour 2 litres of gold plating solution into the beaker then place onto a heating plate and heat it to 60°C. Turn the speed to 5; Set up the DC current source (without load) is about 5 mA.
2. Using the tweezers to hold substrate then hang it to the hook. Ensure the tweezer is in contact with the gold layer of the device by using the multimeter to measure the resistance. Only deep the substrate into the gold plating solution when temperature of the solution is 60°C.
3. Turn power on; turn the voltage knob to get the limited current.

The plating current is about 5 to 5.5 mA. It depends on the plating area.

4. Turn off power when time-up and take substrate out of the bath, wait for about 1 minute for cooling the substrate before wet it with water then dry with nitrogen air. Plating time depends on thickness of the gold layer required and plating area. Normally
 - 1:0 → 4 μm
 - 1:20 → 5 μm

5. After this process, the device must be carefully checked under microscope. If every thing is good (no short circuit, uniform plating, etc), then bake it in the 90°C vacuum oven in about 10 minutes.
6. Measure thickness of gold and PR layers using Talystep.
7. Lift off PR layer by acetone (**must** use the ultrasonic cleaner)
8. Bake it in the 90°C oven in about 10 minutes before doing Au and Cr etch

2.4.3.2 Process 11: Chrome (Cr) and Gold (Au) etch

1. Repeat process 3 using photo-resist AZ4620
2. Repeat process 4 using electrode pattern and reverse mask
3. Au etch (using the substrate holder to hold substrate)

a) Making Au etchant:

The waste gold around the electrode is removed by etching in a very fast Au etching solution. It consists of: 1 part of HNO₃ and 3 parts of HCl

The gold etching solution **must be stored** in an open container due to a possibility of gas explosion. The solution should be left for about 30 minutes or when the colour of solution turning red-yellowish before use.

b) Gold etching: Deep the substrate holder with the substrate into the etching solution, and immediately take it out when the gold start to dissolve. Rinse it with DI water. Etching time is vary, normally it takes about 6-8 sec per 1000 Å⁰; (ii) Dry the substrate with N₂ air .(iii) Checking electrode pattern, if it is good then go to Cr etch, otherwise it is depend on the electrode pattern, then step b can be repeated or remove Au and Cr will be removed.

4. Cr etching

a) Preparing the Cr etchant:

The unwanted Cr around the electrode is removed by using the following solution:

- Ammonium Cerium Nitrate ($(\text{NH}_4)_2\text{Ce}(\text{NO}_3)_6$) : 109.64 g
- Hydrochloric acid 70% (HClO_4) : 85 ml
- DI water : 1 litre

Mix them in a 1.5- litre beaker stirring with a magnetic rod. Using the magnetic hotplate stirrer to mix them for about half an hour, and then store it in a glass bottle.

b) Cr etching:

- Deep the substrate holder with the substrate into the etching solution and take it out when Cr dissolved (it takes about 8-10 sec per 200A°) then rinse it with DI water.
- Dry it with N_2 air
- Check the electrode (under etch, over etch, short circuit, etc)

If every thing is good, then go to 5, otherwise remove all.

5. Bake it in a vacuum oven in about 5 minutes.
6. Using Talystep to measure thickness of the electrode layers.

2.4.3.3 **Process 12: Etching Pads**

1. Repeat process 3
2. Repeat process 4 by using cpw reverse mask, about $500\ \mu\text{m}$ far from each corner of the electrode pattern;
3. Repeat process 10.

After this process, finished optical modulator devices are ready for packaging. All the devices must be checked under microscope the following things before going to fiber pigtail:

- Is there any Au or Cr on the top of the end points the waveguides?
- Is the surface of the two end points are perfectly clean?
- Is there any chip at the end points? If it is then continue to the next processing step.

If the device is clean then store it in a container for pig tailing. If it is not then carefully clean the device by using a cotton tip with acetone and DI water, until every thing is clear and clean. A cross section view of the device and LiNbO₃ substrate for each fabrication process is in figure 5 and figure 6 (from the beginning to the end).

2.5 Fibre Pig tailing and Optical Testing:

2.5.1 Fibre-channel waveguide pig tailing:

This process is very critical. If the waveguide had low coupling loss obtained from waveguide testing, then value of the optical insertion loss now is dependent on the method of coupling the fibre to the MZ waveguide. A schematic diagram of this process is shown in Figure 2. These steps developed for pig tailing are:

1. Cut the paper (thick) into small pieces (about 2x20 mm). These will be used to apply glue to the edges of the end points of the MZ waveguide.
2. Wax the substrate into the small hole in the substrate holder.
3. Cut the fibre and curve the end face of the fibre by using the slicing machine.
4. Arrange the fibre and the substrate to be pigtailed into position.
5. Move in the fibre close to the edge of the waveguide.

6. Align the fibre until you get the best result of optical insertion loss then move the fibre out (about 10 mm from the waveguide's end) very slowly. Note, do not touch any thing on the stage.
7. Using the small piece of paper and a small amount of glue , then gently apply it to the edge of the substrate and close to the waveguide position. Try to use the amount of glue as small as possible.
8. Move the fibre in and align it with the waveguide to get the same or higher output power as before. Then shine the UV light into that position in about 1-2 minute.
9. Again do not touch anything while using the UV light (not vibrate), otherwise the optical coupling loss is very high and it is impossible to observe the guided mode at the other end of the waveguide.
10. Repeat all above steps for the other end of the waveguide
11. Remove the substrate from the stage and place it in a box.

2.5.2 Electrical microwave and optical testing:

The measured parameters are: (i) Microwave index (ii) Bandwidth (iii) V_{π} (iv) Optical coupling loss. Several devices have been fabricated and tested. Illustration of the lithography and fabrication of electrodes, waveguide structures and MZIM is shown in Figure 3 and Figure 4.

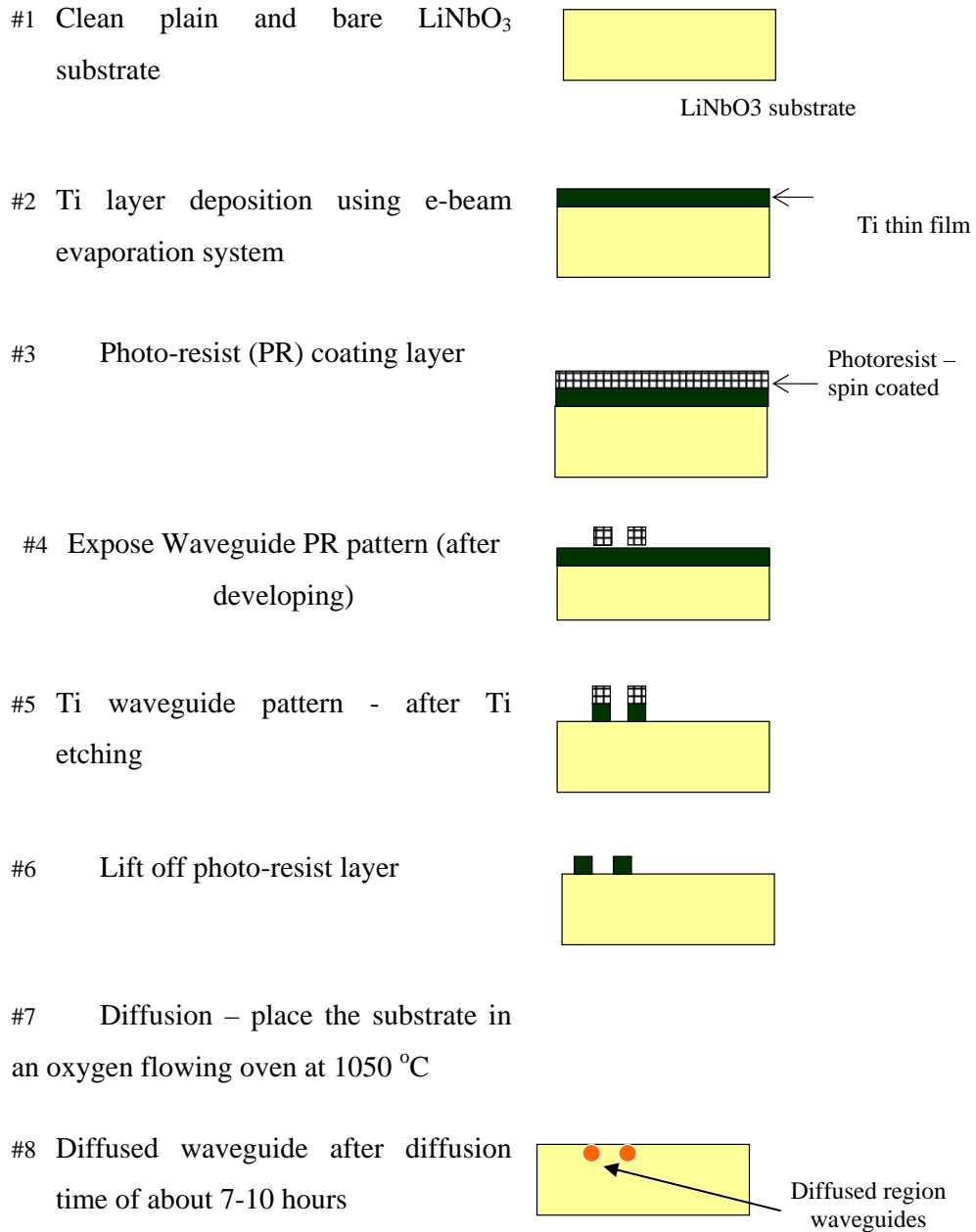
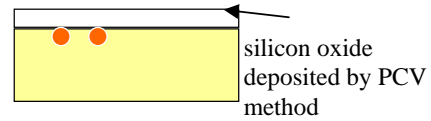
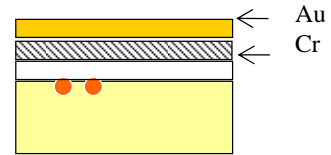


Figure 3: Cross-section view of device of all steps for fabricating Ti:LiNbO₃ Mach - Zehnder waveguide

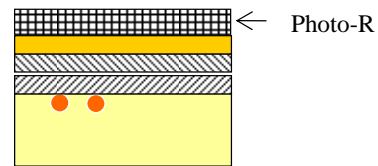
3. SiO₂ layer (deposited by PCV)



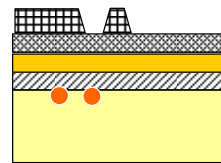
4. Deposition of Gold and Chrome layers



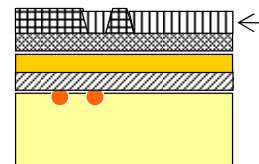
5. PR layer (AZ 4260) (coating by Spinner)



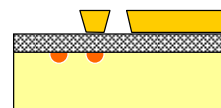
6. Exposing electrode pattern (PR)



7. Device after gold electro-plating



8. Finished final gold plated electrodes and optical waveguides of MZIM



Note: observe the tilted wall structures

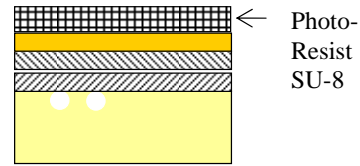
Figure 4 Electroplating of electrodes on optical waveguide structures.

9. DEEP X-RAY FABRICATION PROCESS FOR THICK ELECTRODE ELECTROPLATING

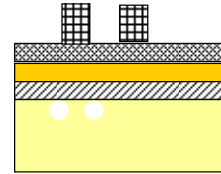
The problems of electroplating thick electrode can be observed from the tilted wall angle shown in Figure 4. This is inevitable as the electroplating is conducted with a thin Au film and without “guiding slots” which can be formed with polymeric film structures and etched with X-ray radiation. This process is usually called LIGA process. In this process a thick polymer film is coated and patterned into a guiding slot for electroplating.

X-ray radiation usually emitted from synchrotron light source can be used as the deep X-ray source. A typical deep X-ray lithography is shown in **Figure 7** and Figure 8. The facility is the lithography beam line of the Singapore Synchrotron Light Source. We have fabricated some test patterns as shown in **Figure 7**. This demonstrates that thick guiding slot polymer can be formed for electroplating of thick electrodes for ultra-wide band optical modulation.

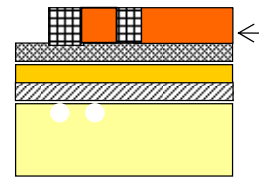
10. PR layer (AZ 4260) (coating by Spinner)



11. Deep X-ray radiation and etching



12. After gold electro-plating



Finished final thick gold plated electrodes and optical waveguides of MZIM. Note: observe the tilted wall structures

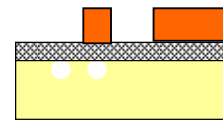
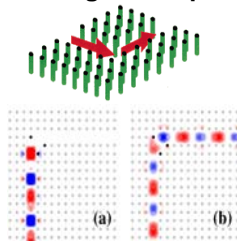
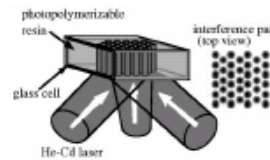


Figure 5 Electroplating of electrodes using the thick “guiding slot” patterned by deep X-ray radiation.

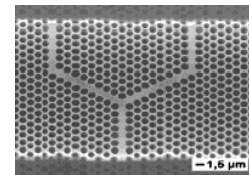
Electromagnetic modelling techniques and



Novel fabrication



Waveguiding in photonic



SYNCHROTRON-RADIATION ASSISTED LITHOGRAPHY (LIGA)

Figure 6 Synchrotron radiation process for fabrication of microwave travelling electrode, especially polymeric structures for electro-plating.

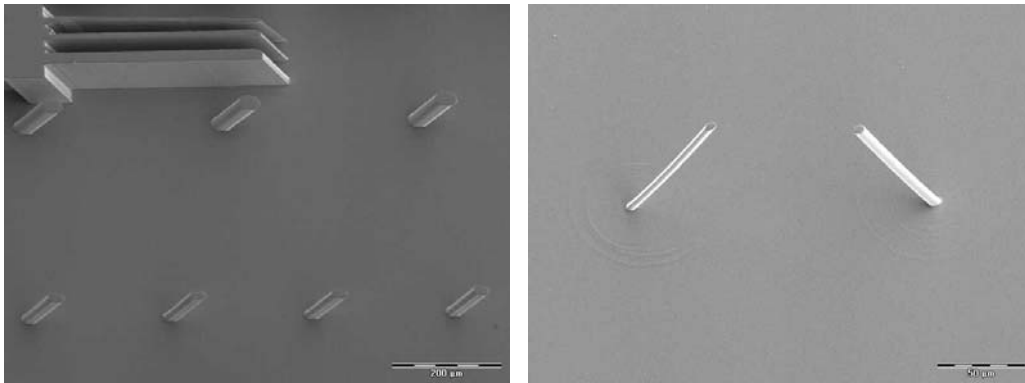
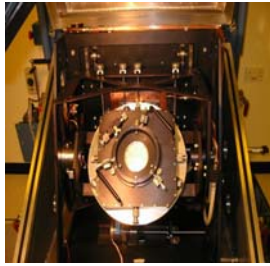


Figure 7 X-Ray Lithography: inclination X-ray radiation on SU-8 polymer – single and angled inclination exposure - Processed at SSLS as a test for fabrication of integrated photonic devices.

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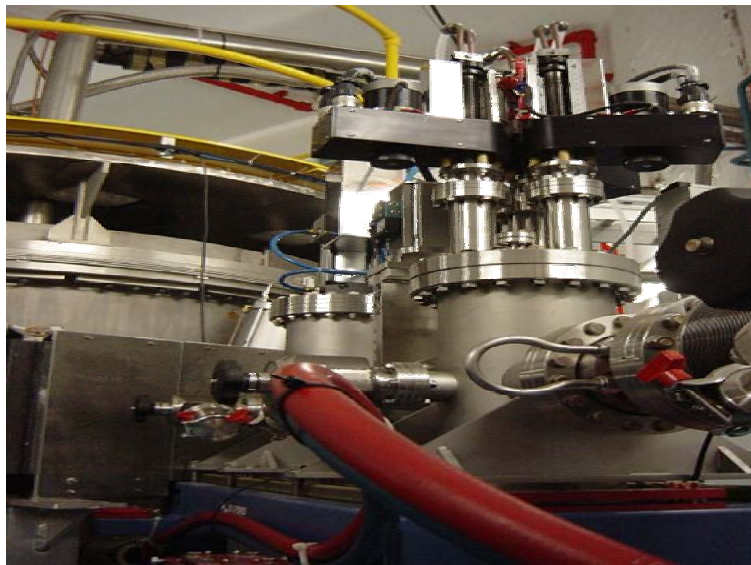
Oliver WILHELM - s/swo@nus.edu.sg , LN Binh and Allan SAW



Bemline LIGA X-ray lithography



Clean room processing



X-ray LIGA lithography beam line arrangement

Figure 8 Facilities at LiMiNT for Lithography for Micro- and Nano-Technology. Proposed techniques for fabrication of integrated photonic devices including the ultra-broadband modulators MZIM.

13. CONCLUDING REMARKS

We have described the fabrication process using optical lithography and deep – Xray lithography for the ultra-wideband optical modulation devices with interferometric optical waveguides and the asymmetric or symmetric electrodes to generate appropriate fields for electro-optic interaction. The processes are simple and should be implemented in standard laboratory for microelectronic and X-ray lithography. Further the procedures for the modelling and design of the optical waveguides and travelling wave electrode structures are described.

The X-ray deep lithography using synchrotron radiation would be a very potential technique for producing “brick wall” like thick electrodes for mm-wave region optical modulation.

Acknowledgement:

The author acknowledges the contribution to the development of the simulation package by TW Chua, A. Le (B.E.) and A. Dang (Assoc. Dip. Fine Mech Eng.) for the fabrication of the modulators and running some simulations. The association of this work with the Singapore Synchrotron Light Sources is greatly appreciated.