ALL-POLYMER BASED FABRICATION PROCESS FOR AN ALL-POLYMER FLEXIBLE AND PARALLEL OPTICAL INTERCONNECT

by

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Abstract

This thesis proposed and demonstrated a new all-polymer based fabrication process for an all-polymer flexible and parallel optical interconnect cable having a vertical light coupler, which can not only cut down the cost by eliminating metallization process for alignment but also facilitate both in production and application. Throughout the process, polyimide was used as the substrate, coated by Epoclad as claddings, then AP2210B and WPR 5100 were used to fabricate waveguides and 45 degree mirror couplers, respectively. In addition, precisely aligned mirror couplers to waveguides are fabricated by using polymer-based, non-metallic, and transparent alignment marks. Conventional and metallic alignment marks are easy to be detected by camera, when a layer of high reflective material, generally Cr metal, is patterned. However, transparent polymer material is used in this process, as alignment marks made of it which are actually buried phase structures. Therefore, it is hardly to be observed by conventional microscopy system. Hence, to increase the contrast of the alignment marks, I proposed and tested a feature specific alignment camera system for which the shape and depth of the alignment marks are optimized for phase-based imaging, such as phase contrast and Schlieren imaging. The results showed a contrast enhancement of alignment marks image compared to that of a conventional microscopy system. By using the fabrication and alignment process, process for adding waveguides to the structure is identified by using the polymer based alignment marks on the WPR 5100 layer. Mask was made by etch down process using fused silica wafer plate, Cr and AZ 3312 photoresist.
At last, the developed and proposed process provides means of all-polymer based fabrication process for a flexible and parallel optical interconnect.
1 Introduction and Overview of Research

Interconnect is often used to transfer data inside and/or among Printed Circuit Boards (PCBs). High performance computing is driving an increasing demand for high speed and energy efficient data transmission solutions. Currently, traditional copper wiring technology is reaching its bottleneck set forth by resistive power dissipation, RC delay, cross-talk and relatively low speed [1]. However, on the other hand, optical interconnects have emerged as a promising solution and are being implemented at ever decreasing distances, for their several advantages such as reduced power consumption, low weight, large bandwidth capacity, independent from impedance and no cross-talk [2]. Over the past decade, routers in data centers and high performance computing systems have adopted fiber optics to meet the rack-to-rack I/O performance requirements. Nowadays, board-level interconnects based on parallel optical channels, where data are simultaneously transmitted along more than one optical channel, have become a preferred interconnect solution over copper cables because of its high data density and transfer rate per cross sectional area.

Recently, flat, flexible and parallel optical interconnects are emerging. A number of optical interconnect architectures have been investigated including multi-core fiber interconnects, optical printed circuit boards, silicon photonics, and hybrid approaches [3]. The devices can accommodate multiple optical channels to sustain high data transfer rate. Figure 1 shows an example of such device [4]. Two circuit boards are connected by a flexible optical interconnect, which consists of two 45-degree mirror couplers at ends that are used to redirect light from vertical direction to horizontal direction, the flexible substrate and the flexible optical
waveguides. For such a device, a low cost fabrication technique is required for the light coupler to redirect light from source to waveguides. Chen et al., reported fabrication of the photoresist waveguide with a coupler on a polymeric substrate by soft molding. The 45-degree coupling mirror is fabricated by mechanically cutting the waveguide with a microtome blade [5]. Direct excimer ablations of waveguide edge, as well as obliquely illuminated mask lithography methods are reported [6, 7]. Recently, Summitt et. al demonstrated a mask-less gray scale lithography process, the maskeless lithography tool be used is a modulated scanning laser system working at 365 nm wavelength, it has a writing stage with X, Y and Z controlled motion, the desired structure can be printed by uploading corresponding bitmap file as a virtual mask. We use a CMOS compatible buffer coat material WPR 5100 (JSR Corporation, Sunnyvale CA) for a 45-degree mirror coupler [8]. The developed process is adopted for my research and the details of fabrication process will be described in the next section. Along with the mirror fabrication technique, polyimide materials such as TOPAS 5013 (TOPAS advanced polymers, Inc, Florence KY) will be used to as flexible substrate while positive gray scale photoresist AP2210B (Fujifilm, Valhalla, NY) can be used for a 10 by 10 μm single-mode waveguides fabrication [9].

Alignment marks are common to be seen in lithographic processes. They help locating the task region, and align a photo mask to the existing features on a substrate. Alignment marks need sufficient contrast to their surrounding features. Therefore, metallic materials, such as Cr are commonly used. In this thesis, we also report detection of phase-based alignment marks to confirm the feasibility of fabrication optical interconnects having polymer mirror coupler along with waveguides by all-polymer process. In addition, a Schlieren imaging microscopy system usable for the alignment purpose is tested as an alternative detection method. Experimentally, contrast of phase structure is evaluated for amplitude detection by detection it regular
microscope to that of phase contrast microscope in reflection mode, and Schlieren-based one as well. The results proved that by employing phase contrast imaging or Schlieren-based alignment process is feasible while using polymer alignment marks buried in the buffer coat material without coating any high reflective metal material.

Figure 1. Structure of flexible optical interconnect
2 Major challenges

To design and fabricate all polymer flexible optical interconnect, we identified that there are three major challenges. First of all, the polymer materials for each part of the optical interconnect need to be determined, the fabrication process sequence also remains unsolved. Second, though other researches has demonstrated how 45 degrees mirror couplers are made by different method on rigid substrate, the feasibility of fabrication on flexible substrate still need to be verified. At the last, due to the proposed polymer alignment process, the method to observe these transparent phase alignment marks is still a challenge because the conventional amplitude based imaging system is not suitable to detect phase objects. In this section, these 3 major challenges for fabrication of all polymer flexible optical interconnect is addressed and the solutions for them are experimentally demonstrated to verify the feasibility of the proposal towards all-polymer process for all-polymer optical interconnect device.

2.1 Materials selection

All the materials proposed and tested here which are polymer materials. The substrate is TOPAS 5013 (TOPAS advanced polymers, Inc., Florence KY) polyimide film, which is transparent and flexible, also its surface is adhesive which can ensure adequate adhesion. Cladding material of the waveguide is Epoclad, a polymer material that is frequently used in photonics communication as cladding. The index of refraction is 1.54. To achieve total internal reflection (TIR) inside the waveguide core, the waveguide material should have higher refractive index than that of the cladding. Two polymer materials, positive photo resist, potentially usable
for the core are considered. Both of the material have higher index of refraction than that of the cladding material. The first candidate material is AP2210B (Fujifilm, Valhalla, NY), a transparent positive photoresist, refractive index of 1.6093. The second candidate material is WPR 5100 (JSR, Sunnyvale CA) which is also a kind of transparent positive photoresist, the index of refraction is 1.679.

WPR 5100 has higher index of refraction than AP2210B. Higher index of refraction for core materials lead to lower loss due to more confined mode structure. In addition to optical properties, to determine the right materials, process sequence also should be taken into consideration. The fabrication of the waveguides and mirror couplers involves two separate exposures and development process. The developer of one photoresist will contact with another material during the development. If it has impact on another photoresist in proceeding process, the following process may destroy the structure of the previous layer. To identify the right process sequence, a dissolve tolerance test is carried out.

First, AP2210B layer is coated on a Si wafer, and the sample is exposure under UV light followed by soaking it into WPR 5100 developer. After being soaked in the WPR developer, almost all the AP2210B layer was dissolved. The results are shown in Figure 2 below. The left side is the photo of AP2210B layer before development under interferometer and the right side is the photo of sample after soaking in the WPR 5100 developer. This result indicates AP2210B can’t be used before WPR 5100, because the later development process of WPR 5100 layer will destroy the AP2210B layer structures. To double check this conclusion, the sequence is reversed to see if AP2210B developer has the same effect on WPR 5100 material. The test process is similar to the previous testing but the materials are inter-changed. WPR 5100 layer is coated first on Si wafer and exposed, then it is soaked in AP2210B developer. The results show that
AP2210B developer does not have significant chemical reaction with exposed WPR 5100, the WPR 5100 layer shows no significant change in surface morphology after the interaction with AP2210B developer. The proposed fabrication order is WPR 5100 layer first followed by AP2210B. Moreover, based on the research done by Summitt and Wong [8], WPR 5100 is a better material to fabricate 45 degree mirror couplers using maskless lithography process as described later. Thus a correct material selection and fabrication process for waveguide and mirror couplers is determined, which is fabricating 45 degree mirror couplers by WPR 5100 material first then fabricating waveguides by AP2210B.
Figure 2. Samples after developing. The first row is the AP2210B layer surface under interferometer, the left side is after exposure, the right side is after developed by WPR 5100 developer, the layer is almost totally removed. The second row the WPR 5100 layer surface under interferometer, the left side is after exposure, the right side is after developed by AP2210B developer, the layer is doesn’t change. The third row is the photo of each sample, left side is the WPR 5100 material after developed by AP2210B developer, the right side is the AP2210B sampler after developed by WPR 5100 developer.
2.2 Fabrication of 45 degree mirror couplers on a flexible substrate

Fabrication of 45 degree micro mirror couplers by using maskless lithography and WPR5100 on a rigid substrate has been reported [8]. Figure 3 shows the cross section of the mirror coupler, by proper exposure process and development recipe, a well-structured 45 degree mirror can be obtained. Based on the results feasibility of fabrication of 45 degree mirror couplers on a flexible substrate is described in this section.

![Cross section of 45 degree mirror couplers fabricated on rigid substrate](image)

Figure 3. Cross section of 45 degree mirror couplers fabricated on rigid substrate [8].

2.2.1 Maskless lithography

The lithography method to print the 45 degree mirror coupler structures is a maskless lithography tool from Prof. Tom Milster’s MLT lab at the University of Arizona [10]. The tool is a modulating and scanning laser system working at 365 nm wavelength. A sample stage with X, Y and Z motion is controlled in synchronous manner to the modulated laser by computer software. The BMP file is used as a virtual mask to control the laser modulation. After manually
adjusting focus of the laser beam by the Z stage, the scanning laser exposes the surface. Bit depth of the bitmap file controls exposure. For example, when a binary bitmap pattern is used, only the white pixel region is exposed while black area not Gray scale BMP pattern enables exposure power modulation based on bit values corresponding to location of sample. A 45 degree mirror couplers on optical interconnect are made by this way to achieve the accurate angle and skip extra steps. Figures 4 shows the system block diagram of the maskless lithography tool.

Figure 4. Block-Diagram of Maskless Lithography Tool [10].
2.2.2 Fabrication of mirror couplers by maskless lithography

The 45 degree mirror couplers are required for directing the light into waveguides, also for output. The material of mirror is WPR 5100, coated on a cladding EPOCLAD layer with specific thickness. To fabricate the mirror strips, maskless lithography tool is applied to print exact structure on this layer, meanwhile alignment cross marks are printed for subsequent steps to print waveguides at correct position. Bitmap pattern is shown in Figure 5. The two mirror strips are placed two side of the layer and perpendicular to the horizontal orientation, five alignment cross marks are designed on top left of this layer. The dark regions have 0 gray value which means these regions are not exposed by the laser, thus these parts will retain after the development.

Figure 5. Bitmap patterns of mirror strips and alignment cross marks
Correct 45 degree angle slope is formed by using the accurate double exposure recipe along with an optimum development time control. Due to the Gaussian profile property of the laser beam, single exposure is attempted however it is hard to get the good 45 degree shape. Also unwanted residual layer at the interface between the mirror and cladding layer exists (shows in Figure 6). To control the mirror shape as well as remove the residual “foot” part, the second exposure is applied to correct the shape of mirror structure and eliminate the residual layer around the mirror structure. For the exposure recipe, the laser power is 200 mV, and do the first exposure for 15 passes in order to obtain mirror strips and cross marks, then do the second exposure for 25 passes to correct the mirror residual “foot” part. For development process, here single development for 8 min in developer 2.8% NMD-3 is employed. Figure 7 below shows the cross section of a mirror strip under SEM. The height of the mirror 2.53 um and the width is 2.59 um, corresponding angle of the slope is 44.32 degree. After the second exposure There is no residual WPR 5100 at the boundary between the mirror substrate and mirror surface. The gold coating process with slit covering on top of the mirror coupler layers is implemented, by this way, gold is coated on the mirror surface to make it high reflective but without coating any other unwanted area.
Figure 6. The mirror structure after the first exposure. The shape and the angle of slope is not correct. Also, the WPR 5100 residual layer still exists around the mirror.

Figure 7. 45 degree mirror couplers on flexible substrate. The mirror structure after the second exposure, the angle of the slope is almost 45 degree, and there’s no WPR 5100 material left outside the mirror region.
Figure 8 shows the comparison between virtual and physical sample, the arrow aims at the mirror strip structure fabricated on cladding layer which is also coated on a flexible substrate.

![Figure 8. Photo of fabricated WPR mirror couplers layer on flexible substrate.](image)

2.3 All-polymer alignment process

2.3.1 Fabrication of alignment marks by maskless lithography

The alignment marks are fabricated on the same layer and are made at the same time with mirror couplers. When fabricating waveguides after them, alignment marks will be used as the reference to locate the correct position for waveguides with respect to the mirrors. Usually, alignment marks are designed to a cross shape for an accurate alignment. Figure 9 shows the dimensions of the alignment mark.
In the all polymer process, alignment marks are buried in the waveguide material layer. Since both of the materials are transparent, amplitude variation of the reflected light from the interface is small. Between the WPR5100 and AP2100B, we expect to have 0.06% of Fresnel reflection, due to the small change in amplitude from the alignment mark region such polymer based cross marks can’t be distinguished from the surrounding background. Thus it is not ideal to use conventional microscope to detect the alignment marks.

To solve the problem phase detection is effective, the phase of light through the alignment mark structure changes because of the refractive index difference between two different materials. Optical path difference at a wavelength of 530 nm is 0.39\(\lambda\), equal to 0.79\(\pi\) phase shift for which phase-based detection methods to observe the transparent buried alignment marks is designed and tested.
2.3.2 Detection methods

2.3.2.1 Phase contrast detection

Phase contrast microscopy was invented by Nobel laureate, Frits Zernike, in early 1930s [11]. It is an optical microscopy technique that converts phase shifts in light passing through a transparent specimen to brightness changes in the image. Phase shifts themselves are invisible, but become visible when shown as brightness variations. The basic principle to make phase changes visible in phase contrast microscopy is to separate the illuminating background light from the specimen scattered light, which make up the foreground details, and to manipulate these differently. The ring shaped illuminating light that passes the condenser annulus is focused on the specimen by the condenser. A part of the illuminating light is scattered by the specimen. The remaining light is unaffected by the specimen and forms the background light. When observing an unstained biological specimen, the scattered light is weak and typically phase shifted by -90° relative to the background light. This leads to the foreground and background having nearly the same intensity, resulting in a low image contrast.

In a phase contrast microscope, the image contrast is improved in two steps. The background light is phase shifted -90° by passing it through a phase shift ring. This eliminates the phase difference between the background and the scattered light, leading to an increased intensity difference between foreground and background. To further increase contrast, the background is dimmed by a gray filter ring. Some of the scattered light will be phase shifted and dimmed by the rings. However, the background light is affected to a much greater extent, which creates the phase contrast effect [12].

The technique is frequently applied in biology field to make it possible for biologists to study living cells and how they proliferate through cell division. Because many cellular
structures are not visible with a simpler bright field microscope, these structures were made visible to earlier microscopists by staining, but this required additional preparation and killed the cells. Similar to the case, in the all-polymer fabrication process, the buried polymer alignment marks are transparent and have only several micrometers depth. Therefore, the light transmitted through them will hardly change its amplitude but shift phase instead. Based on this, phase contrast microscopy in detecting alignment marks is a viable option.

In order to make it works for testing sample which has non-transparent silica wafer substrate, traditional transmission optical configuration is modified to reflective mode microscopy system (Figure 11). A beam splitter is placed to split the incident illumination light and reflection light, and two 4f relay lenses to match the ring annulus and phase plate at the same conjugate plane. In this way, the reflective mode phase contrast microscopy system can function exactly same manner as transmission mode.
2.3.2.2 Schlieren imaging

As an alternative phase detection technique, Schlieren imaging is known to visualize density variations in transparent media. The optical setup of a Schlieren imaging system comprises a parallel illumination beam, focusing element, stop (sharp knife edge) and a camera. The parallel beam is created by a point-like light source (a laser focused into a pinhole is sometimes used) placed in the focal point of a collimating optical element (lens or mirror). The focusing element is a lens or a mirror. The optical stop is a razor placed horizontally or vertically in the focal point of the focusing element, carefully positioned to block the light spot image on its edge. The camera is positioned behind the stop equipped with a lens. The focusing element focus the parallel light into a single point. After passing through the gradient index media, the
rays crossing the focal plane of the focusing element can be divided into two groups: those that interacted with for example air whose index of refraction is modulated and those that didn't. The latter group remains parallel and focus at a point in a well-defined position in the focal plane. The optical stop is positioned exactly at that point, to prevent all corresponding rays from further propagating through the system and to the camera. Thus we get rid of the portion of light that crossed the transparent media without interaction. However, there are another group of rays that did interact with the gradient index transparent media, this ray is deflected and no longer parallel, so it doesn't intersect the focal point of the focusing element and is not blocked by the knife.

Finally, it reaches the camera to create a point-like image on the camera-sensor, with a position and intensity related to the inhomogeneity experienced by the ray, in this way an image with different light intensity level points map is formed [13].

The principle to visualize density variation in transparent media is very consistent with my purpose to observe the transparent alignment marks which has different refractive index from surrounding materials. To verify this concept, a modified Schlieren microscopy system for reflective object was built on the bench table. Differ from the Phase Contrast system, two knife edge were placed at the conjugate plane to block portion of the focusing beam.
2.3.3 Microscopy system design and Modulation Transfer Function evaluation

Based on stock lens, a 5X NA 0.11 microscope objective and several achromatic doublets from Rolyn Optics are used to build the phase contrast microscopy system. Before setting up the system on the bench table, all the parameters of the components are modelled by using optical design software (Code V), to simulate the system performance, specifically resolution by evaluating a modulation transfer function (MTF). Figure 13 shows the 2D layout of the imaging part of the system. The first lens is a perfect lens module used to simulate the objective lens. The object NA is set as 0.11 to match to the NA of the Rolyn lens one. Then a 4f relay system is
entered, the first lens has focal length equal to 100 mm (Rolyn Model #20.1230) and the second one has focal length equal to 200 mm (Rolyn Model #20.1303), to add an additional the magnification. After that, a 50 mm focal length achromatic doublets lens (Rolyn Model #20.1130) is used as imaging lens, and make rays focus on the imaging sensor plane.

![Figure 13. 2D layout of designed microscopy system.](image)

MTF of the lens system is evaluated by Code V. The CCD sensor camera been used as image plane has around 8 um size pixel, thus the nyquist frequency is 62.5 lp/mm. The MTF plot shows below. Need to mention here, due to the finest feature dimension of alignment marks is 20 um and the magnification of system is 5X which can be transfer to spatial frequency equal to 10 cycles/mm, according to the MTF plot, it shows the contrast of all fields at 10 cycle/mm are above 0.8, though the objective lens in the layout is simulated by a perfect lens module, the final image quality should still be good enough for my purpose. Also, spot diagrams for each field of view are provided as reference. Based on this simulation results, the optical system is built on a bench table for imaging testing (Figure 16).
Figure 14. MTF plot of simulated microscopy system, the 10 cycles/mm corresponding to the 20 um object in image plane.

Figure 15. Spot diagrams of the microscopy system when working at different field of views.
2.3.4 Experiment results

2.3.4.1 Phase contrast microscopy system

To examine the imaging performance of the reflection mode phase contrast microscopy system, we made alignment samples. A wafer is coated with WPR 5100 and AP2210B, the marks are in the middle WPR 5100 layer which have a feature of a regular cross, and sink inside. The whole WPR 5100 layer is covered by AP2210B layer. The dimension of the cross is 100 μm in length and 20 μm in width. Figure 17 shows the structure of this regular cross marks. Note: The white part will be removed after exposure. The image of this buried alignment mark was taken from both phase contrast imaging and the conventional imaging system with a 5X magnification under LED illumination with wavelength of 619 nm. The image from conventional detecting
microscope and the image from phase contrast imaging. The contrast of cross mark edge under conventional microscope is only 0.000814 while the contrast under phase contrast is 0.022.

![Image of cross marks and intensity profiles](image)

Figure 16. Bitmap pattern of alignment cross mark (left), image of cross mark under conventional microscopy system (middle), image of cross mark under our phase contrast microscopy system (right). The intensity profile at the edge region of the cross mark under each microscope system shows below, y axis is gray scale value, x axis is distance in pixels.

Contrast of transparent cross mark enhanced much under phase contrast microscopy system. However, the blur of the cross mark edge is obvious, which will decrease the accuracy of alignment. With the edge sharpness problem stated above, a hollow cross pattern is designed to increase the scattering at the edge of the alignment marks in order to enhance the edge sharpness.

Remaining the same system magnification and the same illumination condition, experimental
results of such structure under phase contrast imaging and conventional imaging are shown below in Figure 18.

![Image](image_url)

Figure 17. Bitmap pattern of alignment hollow cross mark (left), image of cross mark under conventional microscopy system (middle), image of cross mark under our phase contrast microscopy system (right). The intensity profile at the edge region of the cross mark under each microscope system shows below, y axis is gray scale value, x axis is distance in pixels.

The result demonstrates the phase contrast imaging has significantly improved the contrast of the buried alignment mark than that of the conventional imaging, the contrast of cross mark edge under conventional microscope is only 0.0054 while the contrast under phase contrast is 0.043772. Also, the hollow structure modification improved the edge sharpness of the cross structure from 0.022 to 0.043772.
2.3.4.2 Schlieren microscopy system

For Schlieren imaging to work, a gradient cross pattern is designed as for testing purpose. The cross alignment marks are made by maskless lithography technology through linearization process, and the gray value of this gradient cross structure ranges from 255 to 64 from left to right. The images were taken with 5X magnification objective lens with LED illumination. Figure 19, shows the image from conventional detecting microscope and the image from Schlieren imaging.

Figure 18. Bitmap pattern of alignment gradient cross mark (left), image of cross mark under conventional microscopy system (middle), image of cross mark under our phase contrast microscopy system (right). The intensity profile at the edge region of the cross mark under each microscope system shows below, y axis is gray scale value, x axis is distance in pixels.
From the experimental result, the Schlieren imaging also shows significant contrast enhancement of the buried alignment marks than that of the conventional imaging, the contrast of cross mark edge under conventional microscope is only 0.00089 while the contrast under Schlieren microscope is 0.063.

2.4 Fabrication of waveguide by mask lithography

To guarantee the correct location and orientation for printing waveguides, waveguide patterns mask with alignment marks is applied. The mask structure is shown in Figure 20. It contains 100 waveguide strips. Note that the dark region is un-exposed while the white region is exposure part. There are also 5 cross marks on the top left of mask for aligning with the bitmap pattern of mirror layer shows in previous section. Differing from conventional mask alignment method, we directly cover the mask onto the wafer once matching the alignment cross marks of both plates by using our home-made phase contrast microscopy system to detect it.
Figure 19. Bitmap pattern of waveguides lithography mask.

A fused silica wafer is used as substrate of alignment mask, then coated with 100 nm of a Cr layer on top by utilizing e-beam evaporate technology. After that, an etch-down is applied. The photoresist AZ 3312 (AZ electronic materials, Sommerville, NJ) is used for fabrication. We exposed the wafer using a maskless lithography technology with uploaded virtual waveguide patterns as well as alignment cross mark patterns, then we put it into developer solution to remove exposure parts, afterwards place the wafer into Cr solution for one minute until the chrome which is under exposure part been totally dissolved, afterwards rinse in D.I water to
remove the residual photoresist material. The whole process flow is shown in Fig 21. Figure 22 shows the physical photomask for waveguide patterns.

Figure 20. Process flow of waveguides mask fabrication.
By employing microscopy systems mentioned above, we can match the alignment cross marks of both mirror and waveguide layers. Once they are matched with each other, the mirror strips are printed in perpendicular and adjacent to the waveguide strips. Bitmap patterns matching figure is shown in Figure 23. The cross marks on top left of both layers are exactly overlapping. Shift the wafer which covered by mask already to the stage under the laser, expose the outer layer for specific exposure time, consequently, take off the mask from top and put the wafer into the developer to remove the exposure part. Proper exposure and developing recipe still need to be determined in order to obtain well shaped 10 by 10 μm single-mode rectangular waveguides.

Figure 21. Waveguide photomask.
However, at this point, we found that it’s hard to achieve well-defined rectangular shape waveguides, due to the Gaussian beam property of the writing beam. The Figure 24 shows the result of waveguide structure cross section after mask lithography process, the expected rectangular shape results in keystone shape, this indicates the difficulty of use of MLT to fabricate well defined rectangular structure especially with low Gamma photoresist such as AP2210B. An optimal exposure recipe or a better alternative material still need to be determined to obtain well-defined waveguide structure.

Figure 22. Bitmap pattern when mirror strips and waveguide strips matching with each other.
Figure 23. Cross section of waveguide structure under SEM. The shape change from rectangular to keystone due to the Gaussian beam property of the exposure source.
3 Process flow

Section 3 addressed major three challenges and solutions to show the feasibility to fabricate well-defined shape of waveguides by photomask lithography process, towards all polymer based fabrication process for all polymer flexible optical interconnect. Figure 4.1 is proposed process flow. First of all, a flexible polyimide substrate TOPAS 5013 is supported by a rigid substrate such as Si wafer during process. Then, a layer of cladding material, Epoclad (Micro resist technology, Berlin Germany), is coated as bottom cladding of waveguides. As mentioned in Section.1, WPR 5100, a positive photoresist material, is applied to fabricate mirror couplers, as well as alignment cross marks for aligning waveguides in the later process. After coating the WPR 5100 layer on top of the cladding layer, mask less lithography is employed to expose the mirror and alignment marks followed by development. For waveguide fabrication, a layer of AP2210B is coated. Prior to exposing AP2210B, a Cr-mask for waveguide is aligned in order to target the accurate position for waveguides with respect to the mirror. We used a custom designed phase-based microscopy system to detect the alignment marks which is buried underneath the AP2210B layer.

To achieve fine rectangular strips structure for waveguide, a photomask with strips patterns is applied when exposing. Following development, hundreds of rectangular waveguide strips are fabricated. Finally coating another layer of Epoclad on top forms cladding of waveguides. The last, remove the bottom Si wafer, a flexible optical interconnect based on all-polymer materials is completed. As Figure 26 shows all polymer alignment process eliminated substantial amount of process for alignment marks used for conventional alignment process.
Si wafer
Attached by polyimide tape
Attached by polyimide tape
Coated with cladding material
Coated with cladding material
Coated with WPR 5100 and exposed by maskless lithography tool
Waveguide structures left after developing
45 degree mirror couplers and alignment marks left
Remove Si wafer
Remove Si wafer
Coated with top cladding material
Coated with top cladding material
Coated with AP2210B and exposed using mask lithography
Coated with top cladding material

Figure 24. Process flow of fabrication of flexible all-polymer based optical interconnect.
Figure 25. Comparison between all-polymer fabrication process and conventional fabrication process.
4 Outlook and future research-long polymer

flexible optical cable

Some class of storage and data transfer among multiple devices needs a long distance data transfer, thus a much larger area and much longer length optical interconnect is desired. However, it’s not possible to fabricate this long optical interconnect through the conventional process limited by exposure area, typically on the order of several inches in lateral dimensions at maximum. The challenge can be mitigated by a roll-to-roll lithography process, and is designed as solution for high-speed large-area nanoscale patterning with greatly improved throughput. The basic idea of this process is twining long flexible polyimide film around the rolls in the system. When all rollers start rotating towards one direction together and at the same speed, the film which acts as flexible substrate will be sent to the coating and printing stage continuously by controlling the rotation speed properly, all area of the long film can get exact required exposure time. Figure 27 introduced one example of the roll-to-roll UV-exposure lithography process [14] Tt includes two main parts: (1) the coating process and (2) the imprinting-curing process. First, a liquid phase UV-curable resist material is continuously coated on flexible film by a three-step roller coating system. The coating system is synchronized with the main imprinting roller to guarantee uniform coating thickness regardless of web speed.
Based on my own all-polymer based flexible optical interconnect fabrication process, a modified roll-to-roll lithography process is designed.

Step 1: coating and baking

Figure 26. Roll-to-roll UV printing process [14].

Figure 27. Roll-to-roll coating and baking system
Because AP2210B material need soft bake after coating, the first step should be roll-to-roll coating and baking process. The first rotating roller at the right side function as supply roller to guide the polyimide film into the AP2210B pond, the film itself will adsorption the photoresist material on its surface, and then squeezed by the two adjacent rollers due to the pressure AP2210B layer can get the required thickness. And the coated film will be sent all the way to the heater stage. The temperature of heater is set as required for soft baking, the rotation speed of the roll depends on the length of the heater stage to make sure all the coated region can be baked for proper duration. Here, for AP2210B soft baking, we need 115 degrees for 3 min, hence the rotation speed of rollers should be set as L/3 mm/min.

Step 2: printing

The AP2210B layer is sent to exposure stage after soft baking by rollers. The waveguide patterns photomask is mounted above the film and UV laser with proper power keep exposure through it. AP2210B which is a positive photoresist will change its chemical property once getting exposure by UV light. In case there may be some slack in between two rollers which will cause the error of the waveguides shape, exposure stage should be close to one roller side, because at that part the film is tight. As well as coating and baking process, rollers’ rotation speed should be set properly to meet the required exposure time.
Figure 28. Roll-to-roll lithography system.

Step 3: developing

The film is sent to the AP2210B developer pond after exposure, the AP2210B material developing recipe is 1 min 30 second, so here the rotation speed of rollers should be \( \frac{C}{90} \text{ mm/s} \), \( C \) is the arc length of the immersed roller part. After developing, the 30 meter waveguide structures on flexible polyimide film are obtained.

Figure 29. Roll-to-roll photoresist developing system.
5 Conclusions

An all-polymer lithography process to fabricate the flexible optical interconnect having a vertical mirror coupler is proposed. Maskless and mask lithography techniques are simultaneously used to fabricate 45 degree mirror couplers and waveguides on a flexible substrate. Transparent polymer material used alignment marks has an intrinsically low amplitude reflection, therefore conventional alignment camera is not suitable for alignment purpose. Considering the weak-phase property of such buried and phase alignment marks, an engineered alignment marks combined with phase contrast imaging to achieve the contrast enhancement. Schlieren-based alignment is also tested as an alternative. Experimental results show a contrast enhancement compared to that of conventional imaging. Also solvent tests were implemented, 2 potential polymer materials are coated on Si wafer and do exposure, then send to different developers to see if they have chemical reaction, based on the experiments results, WPR 5100 is determined as mirror couplers material and should be developed firstly, while AP2210B is used to fabricate waveguides later. At last, this thesis also proposes a roll-to-roll fabrication process for long flexible all-polymer optical interconnect which can be used in stack-to-stack data transfer.
6 Matlab code for bitmap pattern

1. Waveguide mask gray scale pattern

\[
\text{N3=255*ones(5,3874*2);}
\]
\[
\text{F =zeros(10000,10000);}
\]
\[
\text{for i = 1:100}
\]
\[
\text{F((2500+(i-1)*50):(2504+(i-1)*50),1500:(1500+3874*2-1)) = N3;}
\]
\[
\text{end}
\]
\[
\text{%waveguides}
\]
\[
\text{N1=255*ones(99,99);}
\]
\[
\text{N2=zeros(33,33);}
\]
\[
\text{for j=1:5}
\]
\[
\text{F(1000:1098,(1500+(j-1)*109):(1598+(j-1)*109))=N1;}
\]
\[
\text{F(1000:1032,(1500+(j-1)*109):(1532+(j-1)*109))=N2;}
\]
\[
\text{F(1066:1098,(1500+(j-1)*109):(1598+(j-1)*109))=N2;}
\]
\[
\text{F(1066:1098,(1566+(j-1)*109):(1598+(j-1)*109))=N2;}
\]
\[
\text{end}
\]
\[
\text{%cross marks}
\]
\[
\text{figure(5)}
\]
\[
\text{imshow(uint8(F));}
\]
\[
\text{imwrite(uint8(F),'C:\Users\Jilin\Documents\MATLAB\CrMask_negative.bmp','bmp');}
\]

2. Mirror coupler double exposure

\[
\text{N2=zeros(2,3874*2);}
\]
\[
\text{N3=zeros(1,3874*2);}
\]
\[
\text{N4=128*ones(1,3874*2);}
\]
\[
\text{F = 255*ones(10000,10000);}
\]
\[
\text{for i = 1:10}
\]
\[
\text{F((2500+(i-1)*98):(2500+(i-1)*98),1500:(1500+3874*2-1)) = N3;}
\]
\[
\text{F((2506+(i-1)*98):(2506+(i-1)*98),1500:(1500+3874*2-1)) = N3;}
\]
\[
\text{end}
\]
\[
\text{for i= 11:20}
\]
\[
\text{F((2500+(i-1)*98):(2501+(i-1)*98),1500:(1500+3874*2-1)) = N2;}
\]
\[
\text{F((2505+(i-1)*98):(2506+(i-1)*98),1500:(1500+3874*2-1)) = N2;}
\]
\[
\text{end}
\]
\[
\text{for i=21:30}
\]
\[
\text{F((2501+(i-1)*98):(2501+(i-1)*98),1500:(1500+3874*2-1)) = N3;}
\]
\[
\text{F((2505+(i-1)*98):(2505+(i-1)*98),1500:(1500+3874*2-1)) = N3;}
\]
\[
\text{end}
\]
\[
\text{for i=31:40}
\]
\[
\text{F((2500+(i-1)*98):(2500+(i-1)*98),1500:(1500+3874*2-1)) = N3;}
\]
\[
\text{F((2501+(i-1)*98):(2501+(i-1)*98),1500:(1500+3874*2-1)) = N4;}
\]
\[
\text{F((2505+(i-1)*98):(2505+(i-1)*98),1500:(1500+3874*2-1)) = N4;}
\]
\[
\text{F((2506+(i-1)*98):(2506+(i-1)*98),1500:(1500+3874*2-1)) = N3;}
\]
\[
\text{end}
\]
for i=41:50
    F((2500+(i-1)*98):(2500+(i-1)*98),1500:(1500+3874*2-1)) = N4;
    F((2501+(i-1)*98):(2501+(i-1)*98),1500:(1500+3874*2-1)) = N3;
    F((2505+(i-1)*98):(2505+(i-1)*98),1500:(1500+3874*2-1)) = N3;
    F((2506+(i-1)*98):(2506+(i-1)*98),1500:(1500+3874*2-1)) = N4;
end
figure(5)
imshow(uint8(F));
imwrite(uint8(F),'C:\Users\Jilin\Documents\MATLAB\negative_foot_modification.bmp','bmp');

3. Waveguide and alignment marks

n = ones(48,48);
len=1;
increment = length(n)/len;
for ii = 1:48
    n(:,((ii-1)*len+1):(ii*len))= (160-(ii-1)*(128/(4*increment/3)))*
    n(:,((ii-1)*len+1):(ii*len));
end
n(1:20,1:20) = 0;
n(1:20,28:48)=0;
n(28:48,1:20)=0;
n(28:48,28:48)=0;
n1= zeros(64,64);
n1(9:56,9:56) = n;
figure(1)
imshow(uint8(n1));
% two alignment marks separation is 8mm ~ 3810 pixels(1 pixel = 2.1um)
N = zeros(64,3874);
N(:,1:64) = n1;
figure(2)
% imshow(uint8(N));
N1 = repmat(N,1,2);
N1(:,64:3874) = 255;
N1(:,(3874+64):end) = 255;
figure(3)
% imshow(uint8(N1));
N2 = zeros(7,3874*2);
figure(4)
% imshow(uint8(N2));
% combine all sections strip = 6 pixels
F = 255*ones(10000,10000);
F(2000:2063, 2000:(2000+3874*2-1)) = N1;
for i = 1:30
    F((2500+(i-1)*30):(2506+(i-1)*30),1500:(1500+3874*2-1)) = N2;
end
figure(5)
imshow(uint8(F));
% square-well pattern for foot modification
N3 = ones(2,3874*2);
F1= zeros(10000,10000);
for j = 1:10
    F1((2500+(j-1)*30):(2501+(j-1)*30),1500:(1500+3874*2-1)) = 255*N3;
    F1((2505+(j-1)*30):(2506+(j-1)*30),1500:(1500+3874*2-1)) = 255*N3;
end
```matlab
for jj = 11:20
    F1((2500+(jj-1)*30):(2501+(jj-1)*30),1500:(1500+3874*2-1)) = 196*N3;
    F1((2505+(jj-1)*30):(2506+(jj-1)*30),1500:(1500+3874*2-1)) = 196*N3;
end
for jjj = 21:30
    F1((2500+(jjj-1)*30):(2501+(jjj-1)*30),1500:(1500+3874*2-1)) = 128*N3;
    F1((2505+(jjj-1)*30):(2506+(jjj-1)*30),1500:(1500+3874*2-1)) = 128*N3;
end
figure(6)
imshow(uint8(F1));
imwrite(uint8(F1),'ModifiedAlignmentmarks_micromirror30pieces.bmp','bmp');
imwrite(uint8(F1),'mirrorfootmodification_threedepth_10pieceshassamedepth.bmp','bmp');

%%This is gradient cross assigned with bitmap value from 255 to 64, so the
%%right end is not completely black
```
7 Reference


List of Publications

1. Jilin Yang, Tao Ge, Chris Summitt, Sunglin Wang, Tom Milster, Yuzuru Takashima, ”All-polymer based fabrication process for an all-polymer flexible and parallel optical interconnect”, Submitted for SPIE Optics and Photonics, Nanoengineering: Fabrication, Properties, Optics, and Devices XII (2015)(http://dx.doi.org/10.1117/12.2187143)

2. Tao Ge, Jilin Yang, Chris Summitt, Sunglin Wang, Lee Johnson, Melissa Zaverton, Tom Milster, Yuzuru Takashima,” High contrast and metal-less alignment process for all polymer optical interconnect devices”, Accepted for SPIE Photonics West, MOEMS-MEMS, Advanced Fabrication Technologies for Micro/Nano Optics and Photonics VIII (2015)