2006-313: A MASKLESS FABRICATION APPROACH OF INTEGRATED OPTICAL WAVEGUIDES FOR ENGINEERING TECHNOLOGY STUDENTS

Shuping Wang, University of North Texas

Vijay Vaidyanathan, University of North Texas
A Maskless Fabrication Approach of Integrated Optical Waveguides for Engineering Technology Students

Introduction

The optical waveguide is one of the fundamental components for optical integrated circuits\(^1\). The current technique used to fabricate polymer waveguide devices is mainly based on spin coating and photolithography patterning\(^2\). The technique requires fixed photomasks, which are inherently expensive and unaffordable for many engineering and engineering technology programs. Maskless writing techniques, including electron-beam direct writing\(^3\,^4\), ion-beam direct writing\(^5\), X-ray lithography\(^6\,^7\), and laser direct writing\(^8\,^9\), are alternate polymer waveguide fabrication approaches. Due to their high operation cost, first three maskless technologies are not suitable for teaching purpose. This paper presents a simple and inexpensive polymer optical waveguide fabrication approach, i.e. Laser Direct Writing (LDW), developed for our ELET 5320 (Introduction to Telecommunications) course. LDW waveguides will be produced in a single computer controlled step. This process eliminates all the complex steps associated with the definition of structures using photolithographic techniques. The development of this project would enable students to gain similar experience on photolithography with equipment that costs much less.

The polymer waveguide fabrication technique demonstrated in this paper could also be adopted by other engineering technology programs for courses in manufacturing, semiconductors, and microfabrication. The theory behind the polymer waveguide formation, i.e. LDW, introduced in this paper is identical to that of the photolithography technique. The waveguide fabrication processes (spin coating, photo resist developing, etc.) are the same for both approaches. We demonstrate that with the alternate and inexpensive approach of the LDW, the same quality level of student learning on integrated waveguide fabrications is achievable. We anticipate that concepts and experiences students gain through the project will prepare them to be job ready and productive from day one of their employment.

Laser Direct Writing Technology

LDW is a maskless, low-cost, approach for polymer micro structure fabrication. To fabricate a waveguide, the laser sensitive photosensitive/polymer is spin coated on a substrate. Waveguide patterns are written by tracing a laser beam through objective lenses, which control the beam size and consequently the micro patterns’ size across the surface of the polymer film. The film will then be developed to remove the unexposed area. Combined with other equipment (substrate cleaning equipment, photoresist spinner, etc.), the fabrication system allows students to experience the entire polymer waveguide manufacture life cycle, including the selection of materials, substrate preparation, polymer spin coating, laser direct writing, waveguide inspections, etc.

Polymer Waveguide Fabrication Using Laser Direct Writing Technique

Polymer waveguides are multilayered structures which consist of the lower cladding layer, the core layer, and the upper cladding layer as depicted in Figure 1.
Photolithography is the technology used by the conventional polymer waveguide fabrication. In this process, geometric patterns are transferred from a photomask to the surface of a substrate. The procedures involved in the photolithographic process are (1) substrate cleaning, (2) lower cladding layer formation, (3) waveguide core layer formation which includes photoresist application, photomask alignment, and exposure and development, and (4) upper cladding layer formation. Due to the high-cost of the photomask generation process involved in procedure (3), most engineering technology programs cannot afford the photolithography manufacturing capability. Typically, only theoretical presentations on the polymer waveguide fabrication are introduced to students.

In order to provide students the opportunity to apply the engineering skills they are learning to a practical application to strengthen and expand their learning process, we developed a cost-effective polymer waveguide fabrication process by replacing step (3) above with a less expensive fabrication system - LDW. The procedures/sequences diagram for the LDW of polymer waveguides is depicted in Figure 2 for easy reference, and it is explained further in the following paragraph.

Adhesion of the film to the substrate and the uniformity of the film depend in large on the cleanliness of the substrate. Therefore substrates need to be cleaned with great care. The cleaning of substrates is performed in procedure (1). In procedure (2), a thin film of the photoresist material used for lower cladding is produced by spin coating the photoresist onto the cleaned substrate. The lower cladding layer is formed after the thermal and/or ultra violet (UV) light curing. The procedure (3) is the waveguide formation process which includes the spin coating for the photoresist thin film, LDW of the waveguide, and the sample development. The procedure (4) is necessary only when upper cladding layer (other than air) is desired. The process for this procedure is identical to that of the procedure (2).
Experiments

Following the procedures described in previous section, polymer waveguides are fabricated using LDW technique. The sample fabrication details are explained in following paragraphs.

1. Cleaning of substrates

Substrates used in this work are 1mm thick transparent BK7 micro slides/Si wafers. They are cleaned carefully by following procedures that are illustrated in Figure 3. First, substrates are soaked in Branson optical cleaner solution for 12 hours, followed by 10 minutes ultrasonic bath (Branson 2510 Ultrasonic Cleaner) in the cleaner solution. Substrates are then rinsed thoroughly in deionized water, again followed by 10 minutes ultrasonic bath in deionized water. Finally, each side is blow dried using compressed nitrogen, followed by baking in the oven at 100°C for 24 hours. The substrates are then deemed ready for further fabrication processes.
2. Formation of cladding layers

The lower cladding material used in this experiment is the Norland Optical Adhesive 61 (NOA61). NOA61 is the clear liquid photopolymer with maximum absorption between 350 and 380 nanometers. NOA61 can be cured when exposed to UV light. Curing time depends upon the thickness of the film and the energy of the UV light available.

The Headway Research, Inc. photoresist spinner, depicted in Figure 4, is used for thin film coating. Spinning speeds, spinning time, and acceleration/deceleration are programmable. Spinning speeds are adjustable from 50 to 10,000 rpm. Various vacuum chuck sizes are available to load wafer diameters from 1 inch up to 6 inches.

![Figure 4. Headway Research, Inc. PWM32-PS-R790 Photoresist Spinner](image)
One drop of NOA61 is applied to the pre-cleaned substrate that is mounted on the spinner’s vacuum substrate holder. Lower cladding film is formed by spinning the substrate at the proper speed, e.g. 4000 rpm for a thickness of about 5 µm. The spin coated lower cladding film is cured by exposing it to an UV chamber for 5 minutes. The sample is then ready for further process. As mentioned earlier, the lower cladding layer formation process could be used for upper cladding formation if upper cladding layer other than air is desired.

The thickness of the film obtained by spin coating is determined mainly by the solution viscosity and the spin speed. Film thickness by spin coating is reproducible therefore the experimental calibration curve can be used as the reference for desired film thickness. The relationship between the film thickness and the spin speed for NOA61 and NR7-6000P (the core material which will be explained in the next section) is carried out for calibration purpose, and the result is shown in Figure 5. Film thicknesses are measured by creating a scratch with a knife edge and measuring the step depth using a profilometer. We reference calibration curves in Figure 5 as the spin speed selection guideline for NOA61 and NR7-6000P thin film formations.

![Figure 5. Thin film thicknesses vs. spin speeds](image)

3. Waveguide Core Formation

The fully automated LDW polymer waveguide fabrication system, depicted in Figure 6, is built in the Advanced Optics and Sensors Laboratory at the Department of Engineering Technology. The fabrication system consists of following major components: the laser source - a 6 mW, 375 nm wavelength laser diode module; a beam shutter that is placed on the optical path to temporally block the laser beam during the writing break; the mirror which is used to direct the laser traveling direction; the beam expander and 10x objective lens for beam focusing, and the XY precision stage which is capable of operating at mechanical resolutions of 10nm and repeatabilities of ±100nm. The translation stage’s movement and the beam shutter’ operation are programming controlled using LabView software. Focused laser beam size can be calculated by the equation: \( d = \frac{4f\lambda}{\pi D} \), where \( d \) is the focused beam size (at \( 1/e^2 \) of the peak power point), \( \lambda \) is the laser wavelength, \( f \) is the lens’s focal length, and \( D \) is the \( 1/e^2 \) diameter of the collimated laser beam entering the focusing lens. Calculated beam size, which decides the minimum waveguide size, is less than 3 µm.
The negative photoresist, NR7-6000P\textsuperscript{11} is chosen for core material. To form a thin film, NR7-6000P is spin coated on the substrate coated with the cladding layer at a speed of 4000 rpm. The thickness of the film is about 5 \( \mu \)m based on the experimental result shown in Figure 5. The sample is then placed to a 150\(^\circ\)C hotplate for three minutes softbaking before it is transferred onto the XY translation stage of the LDW system for waveguide pattern formation. Based on the desired pattern geometry, the precision stage is made to travel in appropriate directions with proper speed while exposed to the laser beam. The traveling speed of the substrate is determined by the kind of the photoresist used and the power of the laser source. The post exposure baking is followed by placing the sample on the 100\(^\circ\)C hotplate for three minutes before it is developed. After exposing to the UV light, the negative resist becomes polymerized, and more difficult to dissolve. Therefore, during the developing process the exposed portion of the negative resists remain on the substrate, the developer solution washes off only the unexposed portions. The sample is developed by spray the resist developer onto the sample or by immersion of the sample into the resist developer for 60 seconds (for a 5 \( \mu \)m thick film). The sample is then thoroughly rinsed in deionized water before blow drying by compressed nitrogen or by spinning at 4000 rpm for 40 seconds. 

For demonstration purpose, Figure 7 illustrates the scanning electron microscopy (SEM) micrograph of typical polymer waveguides on a Si substrate. The image shows a top view of two paralleled waveguides with very smooth surface, especially a very smooth waveguide/substrate interface edge. The scattering losses caused by roughness at the top/bottom and side interfaces are usually used for waveguide fabrication quality evaluations. We could not find papers on waveguide fabrications using the NR7-6000P with the photolithography technique for direct comparison. However, by examining the image of the waveguide surface and the edge, we believe the quality of the waveguide is comparable to that of the waveguide fabricated by the conventional photolithography technology.
Conclusions

The LDW is a maskless approach of polymer waveguide fabrication. Therefore, no additional cost, after one time capital investment, is needed for writing different patterns. The pattern definition is implemented by modifying the software program which controls the laser’s movement relative to the substrate. The flexibility for pattern’s modification is especially useful for teaching purpose by enabling the students to enter different values and observe the effect on the written patterns.

The LDW fabrication could be appropriate for both graduate and undergraduate courses. For example, the project assignment for graduate students would combine the device design, fabrication, and characterization together. For undergraduate students, the project assignment could be the waveguide fabrication alone.

The objective of the LDW project is to provide students the opportunity to enforce what they have learned in the classroom through implementation activities which otherwise would not be available to them. In the 2005 fall semester, for the first time we took a graduate (ELET 5320) class of nine students to the Advanced Optics and Sensors Laboratory for practical experiences. Students observed demonstrations of the polymer waveguide fabrication process. This is the first step to fulfill our objective. We plan to divide future classes into small groups of 3-5 students. Each group would fabricate the waveguide based on their designs. We anticipate measurable achievements in following years.

Acknowledgement

Authors thank Brad Borden and Haritha Namduri for taking the SEM image.
References


10. https://www.norlandprod.com

11. http://www.futurrex.com