Review of ReseaRch
ISSN: 2249-894X
Impact Factor : 5.7631(UIF)
Volume - 11 | Issue - 7 | April - 2022

Y-BRANCH SPLITTER (OPTICAL POWER SPLITTER) - DESIGN AND FABRICATION

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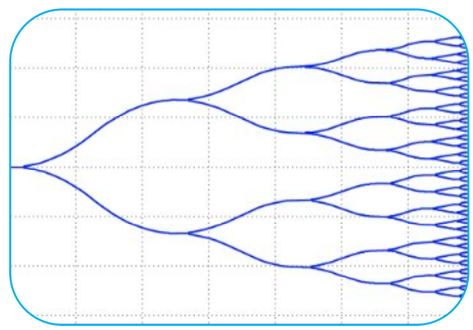
ABSTRACT:

The ever-increasing demand for voice, data, and video services in optical access networks will require broadband optical splitters capable of broadcasting and distributing optical signals from the central office to many users (Okada 1997). The broad-band passive optical network (PON) is an important access infrastructure that provides a cost-effective fiber-to- the-home service (Maeda 2001). A PLC-based dynamic optical splitter for PON/fiber-to-the- premise networks was reported and aimed at providing carriers with the flexibility to add new subscribers to an optical network without the need for traffic disruption that usually results from upgrading optical splitters (Queller 2004). In the subscriber network of a PON, a power splitter is used to distribute optical power from one input channel into several output ones. Multiport power splitters are routinely used in WDM systems. For economical reasons, it is desirable to use passive components for optical signal distribution in broadband WDM communication systems. Power splitters based on branching waveguides are key components for optical signal distribution in hybrid or fully optical access networks (Ueda 2001).



KEY WORDS: *optical access networks , passive optical network (PON) , broadcasting.*

INTRODUCTION

A Y-branch waveguide is a fundamental element utilized in deciding the structure and shape of photonic devices and can be symmetric or asymmetric according to the required branching ratio. Y-branch waveguides are essential in PICs both for signal routing and signal processing. They are utilized as power splitters/ combiners in modulators, switches, interferometric devices and semiconductor laser arrays. For the case of symmetric Y-branch, many new structures have been proposed to achieve a low excess loss (Chaudhari 2001) (Yabu 2001) (Hu 1997) (Chung 1990b) (Seino 1987). For the asymmetric case, a wide range of branching ratio with less losses is required (Suzuki 1996) (Lin 1999a). Various passive and active splitter designs have been proposed previously, including a tree of Y-branches PLC splitter (Takahashi 1993), active splitters (Choi 2000) (Jaouen 1999) (Ratovelomanana 1995) using post-amplification to compensate for the splitting loss. Splitters have been realized with Y-branch waveguides (Tao 2008), multimode interference waveguides (Wang 2004), directional couplers (Kiyat 2005), photonic crystals (Frandsen 2004), and others (Chung 2006) (Schuller 2007).

A branching waveguide that has a low branching loss, small and compact overall size, and is easy to fabricate without critical fabrication requirements is said to be an optimum and an efficient structure. In the design of a power splitter reported in this work, the key design parameters considered in device simulation were the branching angle, the type of bend and its length, the overall device length, the final separation of the output ports, etc., which governed the device performance. Both device length and radiation loss of optical waveguide devices are critically determined by the bend and branch requirements. Design and realization of compact and low-loss branches are of great interest in several integrated optics applications.

This chapter discuss the design and fabrication of Y-branch waveguide which is the basis of the optical power splitter. The conventional Y-branch design for a 1 × 4 power splitter is presented in the chapter. The design of mask for fabrication of 1 × N splitters using L-Edit (Tanner Tools) is presented here. The chapter also describes an overview of the micro- fabrication procedures and techniques for polymer waveguides. Finally the details of fabrication process used in this work is presented in the topic.

AIMS AND OBJECTIVES:

1. Characterization of fabricated waveguides and conventional splitter devices
2. Analyses of defects/issues (if any) induced during process of fabrication and propose a solution for the defect/issue.
3. Fabrication and characterization of the device based on proposed design based on analytical results.
4. Comparison of proposed and conventional splitters characterization results.

1.1 Y-Structure Design and Optimization

Optical power splitters, other than cascaded Y-branch (Burns 1990), are commonly implemented using fiber couplers and multimode interferometers (MMI) (Wang 2002) (Huang 1997) (Huang 1998). However, splitters based on evanescent field coupling and MMI principles suffer from the problem of strong wavelength and polarization dependence if using low index contrast material such as polymer, and therefore they are not suitable for broadband applications (Huang 1997) (Huang 1998). On the other hand, although Y-junction optical power splitters are less wavelength and polarization dependent, they suffer from excess loss due to the mode field/wave-front mismatch between the output and input branches (Yulianti 2010). Splitters based on Y-branch waveguides however, are widely used as the structure is simple and the excess loss caused by optical power splitting is low. Optical outputs of a Y-splitter have a uniform splitting ratio when the splitter is fabricated based on a symmetric structure. Splitters with variable optical power splitting ratio find applications in dynamic control and efficient management of optical power in photonic applications. Forexample, the asymmetric power splitters can be used in optical communications to actively distribute light to optical components that consume varying and uneven optical powers.

A conventional 1 × 2 splitter is simply a Y-branch waveguide where two output waveguides are connected to a linear input waveguide. In conventional 1 × N power splitters constructed by cascading Y-branch waveguides (Chaudhari 2001) (Yabu 2001), the overall physical dimensions of the optical power splitter becomes very large as the number of output ports increases. Consequently, it is desirable to develop a new structure for compact, multi-branch, planar power splitters. It must be noted that Y-branch based 1×N splitters (Beguin 1988) (Nourshargh 1989) (Haux 1989) have the advantages of wavelength independence and small insertion loss deviation between output ports when compared with directional coupler type splitters. The performance requirements for the splitters include a low insertion loss, a wide operational wavelength range, a uniform splitting ratio, a low polarization-dependent loss and a compact size. However, the guided wave on a Y branch always loses energy by radiation because of the discontinuous feature of branch structures. Such radiation causes serious problems in circuit performance due to the undesired power coupling or crosstalk with neighbouring circuits.

1.1.1 Branching Angle:

Burns and Milton introduced a coupled mode equation between branching waveguide modes, and they showed that the Y-branch behaves as a mode-splitter when Y-junction angle is small and it acts as a power divider when the angle is large (Burns 1975). The junction angle should be sufficiently large to avoid coupling of power between output waveguides is negligible. Transmitted power decreases as Y-junction half-angle increases beyond 1º (Anderson 1978). It is well known that Y-branches suffer from severe radiation losses in excess of 3 dB, particularly with a branching angle larger than 2° (Weismann 1989) (Tsutsumi 1988), resulting in poor device performance with respect to contrast ratio and crosstalk. Consequently, for appropriate separation as per standard fibre ribbons between the interacting waveguide arms demands very long dimensions with these narrow branch angles. On the other hand, compact Y-branches that are necessary for high-density integrated optics incur unacceptable losses. The power of the guided mode is divided into branchingwaveguides with relatively small losses when the refractive index difference between the core and the cladding is large (Anderson 1978).

A typical loss figure for a conventional Y-junction splitter is 1 dB with a branching angle of 1° (Yabu 2001). In order to minimize the loss, this angle has to be less than 1°. This then makes the Y-junction to be very long in order to achieve a standard full-pitch spacing of 127 μm between its two output branches. Various methods were recently reported to compensate for such a mismatch (Hung 1988) (Belanger 1983) (Lin 1994) (Lin 1999b) (Gamet 2004) (Wang 2003) (Chan 1996) in order to reduce the junction excess loss with a larger branching angle. In summary, there are two basic approaches to tackle this problem. The first approach is achieved by introducing a wave-front accelerator/microprism in order to compensate the mismatch loss (Hsu 1998). However, this requires more than two different types of index materials and may result in higher fabrication cost. As a result, the fabrication cost would be much higher. The second approach is to modify the physical geometry of the Y-junction directly but, the reduction of loss is not so significant in this case especially at large branching angles.

1.1.2 Output waveguide-bends

Standard splitters that are realized based on Y-junctions design suffer from high reflection and radiation loss due to branching complexity (Chan 1996). It is well known that optical devices using Y-branch structures with abrupt-bend and relatively large branching angles suffer large radiation losses when the refractive index difference between the core and the cladding is small. However, a large index difference makes the fabrication difficult. Also there have been situations where Y-branches with small index difference are found more suitable from the viewpoint of coupling efficiency with other optical devices in integrated optics (Min 1997). Studies have been performed showing the relationship between the angle of the bend and the losses encountered. Bends of less than 3° exhibited losses of less than 1dB, while bend angles 4° and higher showed exponentially growing losses of greater than 1dB (Eldada 1996).

A more compact Y-branching waveguide results with the introduction of some curvature in the arms in the form of an S-bend segment. If such S-bend segments were replaced by linearsegments, such a waveguide design would be arbitrarily long (Ladouceur 1996). The types of S-bend structures available in the opto-electronic CAD software BeamPROPTM include the arc type S-bend, Cosine type S-bend and the raised Sine S-bend. For the design of a low-loss Y-branching waveguide, one has to investigate the dependence of the type of S-bend. From the parameter scans of the type of S-bend, optimized designs for Y-branching waveguides were obtained. The Cosine type S-bend gives the lowest branching loss and the largest output power in its arms (Sum 2004).

The performance of Y-branches, is also affected by interference effects between the guided mode and the field radiated from distortions in the input section, e.g., a fiber-waveguide interface or a bend in the input waveguide as required in cascaded splitter devices. These effects impart an oscillatory dependence to the splitting ratio on wavelength and have been noted both theoretically and experimentally (Munowitz 1992) (Chu 1991) (Deri 1988) (Johnson 1984). The interference effects can be minimized by using long straight waveguides for the input section, as the intensity of radiated modes decreases with growing distance from the perturbation. Long input waveguides, however, result in an inacceptable length of complex devices. An optimal splitter design should combine a short length with a low loss and low sensitivity to distortions like those described above.

1.1.3 BPM Simulation: 1 × N Splitters

A conventional Y-branch waveguide structure consists of a single input wave guide and two output waveguides. Y-branches used for power division are easy to design and are fairly insensitive to patterning tolerances (Tsai 2003). Fig. 3.1 shows a Y-branch schematic. It follows from the symmetry of the Y-branch structure that it will act as a symmetrical power divider between the output waveguides. Thus, for each of the two output arms the theoretical power splitting ratio is 50:50. The refractive indices of the polymer materials SU-8 2002 and NOA 61 were used as inputs to the BPM software. It is required to find the power transmitted to the output waveguides, the power reflected in the input waveguide and the power radiated from the junction into the surrounding medium. BPM simulations do not involve reflective power measurements; hence we have to restrict the discussion to power transmitted to output waveguides and power radiated at the Y-junction. Also, transmission loss is predominantly due to radiation (Anderson 1978).

Figure 3.1. RSoft CAD schematic of the Y-branch device.

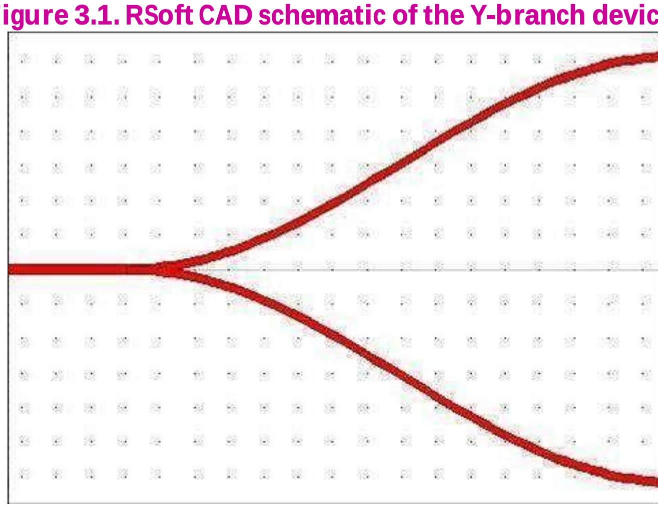
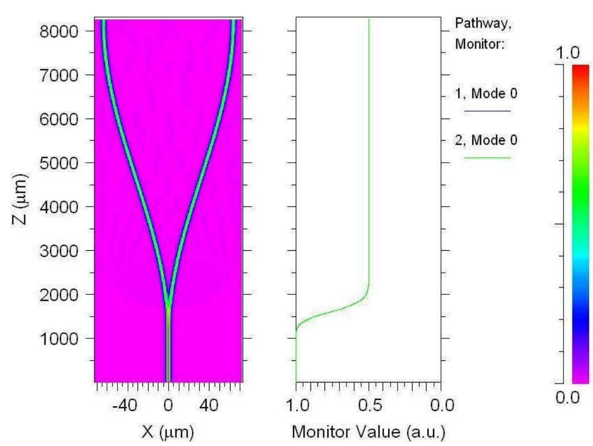


Figure 3.2. Simulation of a 3-dB, 2° Y-branch (a) Designed Y-branch, (b) Performance of the Y-branch



We examine here the transmission performance of a 2D single mode symmetrical Y-junction formed on two cosine-bend waveguides that are connected to a linear input segment using theBPM software, BeamPROPTM. The simulation for a 2° angle for a Y-branch is shown in Fig.3.2. Fig. 3.2(a) shows a top-down view of the device. Light propagation is along the z- direction and the waveguide width is shown along the x-axis. The performance of the Y- branch is shown in Fig. 3.2(b). The input power and the power in the left arm of the Y- branch are shown in blue and that in the right arm is displayed in green. Even though the input power is set to 1, the simulation shows the effects of the 3-dB power distribution, hence the power monitor in green (overlapping blue) shows approximately 0.50 units of the total input power of 1 unit.

Figure 3.3. Simulated 1 × 4 optical power splitter with the outputs

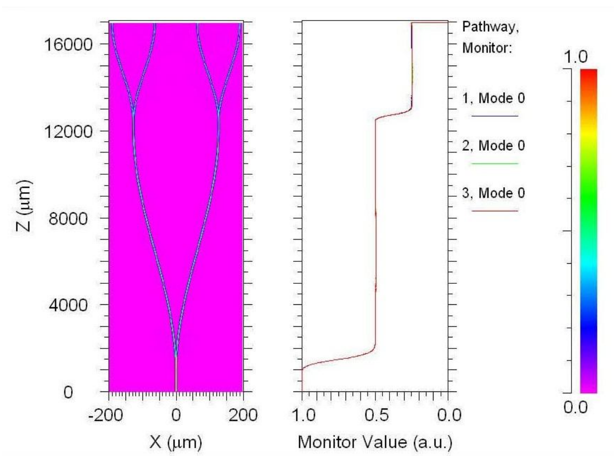


Fig. 3.3 show the designed 1 × 4 optical power splitter and its performance. In all Y- branching arms, cosine S-bends were used to minimize the radiation losses at the splitting junction. The splitting ratio of a Y-branch waveguide depends only on the symmetry and is a wavelength independent 3-dB splitter. The port separation at the output has beenstandardized to 127 μm (center-to-center) so as to match standard fibre ribbon for pigtailing.

In designing an S-bend arm, it is well known that longer arm length leads to better results, since the radius of curvature at the waveguide bends is larger leading to lesser bending loss. However, overall device length on a wafer of given dimensions needs to be kept in mind. Since the polymer layers will be deposited by spinning the polymer solution on the wafer, itcan be assumed that the film will be most uniform in the central region. With this in mind, the splitter length was optimized in such a way that the entire device layout would be in the central region of the spun wafer.

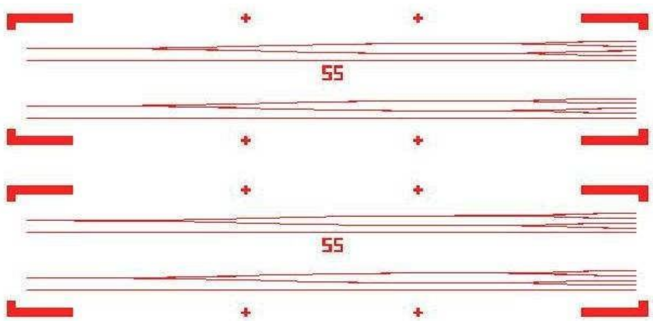
1.2 Mask Design and Development

In contact printing, the resist-coated silicon wafer is brought into physical contact with the glass photomask. The photoresist is exposed with UV light while the wafer is in contact with the mask. Because of the contact between the resist and mask, very high resolution is possible in contact printing. However, a problem with contact printing is that debris, trapped between the resist and the mask, can damage the mask and cause defects in the pattern. The proximity exposure method is similar to contact printing except that a small gap, around 10 microns wide, is maintained between the wafer and the mask during exposure. This gap minimizes (but may not eliminate) mask damage but degrades the resolution that can be achieved from contact-printing. Projection printing (Ashley 1991) (Tumolillo 1991), avoids mask damage entirely. An image of the patterns on the mask is projected onto the resist-coated wafer, which is many centimeters away. In order to achieve high resolution, only a small portion of the mask is imaged. This small image field is scanned or stepped over thesurface of the wafer. Projection printers that step the mask image over the wafer surface are called step-and-repeat systems.

Step-and-repeat projection printers are capable of providing good resolution but for best resolution, contact-printing is still the first choice.

The design results from simulations in previous section were converted to GDS-II format in BeamPropTM. L-Edit (Tanner Tools) was used to design the mask layout. It may be recalled from section 2.8.3 that for a channel waveguide, aspect ratio (w/d) of 1 – 1.125 was chosen so as to yield channel width in the range 2.5 to 3.1 μm for guide thickness of 2.5 μm. In actual fabrication, it is possible that the actual width of the channel may be different from what is present on the mask. With this in mind, 1 × 4 splitters of different channel widths were made in the mask layout. Various channel widths ranged from 1.8 μm to 2.6 μm. Accompanying every splitter of a given channel width was a straight channel waveguide of same channel width. The straight waveguide may be of use in device characterization. Since the photoresist is a negative tone resist, the appropriate mask used was a dark-field mask. Figure 3.4 shows some portions of masks designed in L-Edit with GDS-II format for 1 × 4 splitters.

Figure 3.4. Portions of GDS-II mask schematic for a 1 × 4 splitter



The mask was fabricated by direct-write technique through Laser Pattern Generator (Heidelberg Instruments, Germany) at the Mask Fabrication Facility in CSIR-CEERI, Pilani. The fabricated mask was observed under the microscope to look for defective areas such as pin holes and any other unwanted features.

1.3 Fabrication Techniques for Polymer Waveguides:

In this section, various existing and emerging techniques for the fabrication of polymer optical waveguides will be briefly reviewed. The objective of this review is to provide a broad perspective of the different techniques that are available to fabricate polymer waveguides. The techniques can be broadly categorized into: deposition and etching; direct UV photolithography; casting/molding/embossing; and direct-write techniques. Direct write techniques allow rapid prototyping, are flexible, and can afford precise control over different parameters to create novel structures. However, they produce low-yields and are not suitable for mass-production of devices. Plasma/Reactive-ion etching and embossing techniques too are multi-step processes and time-consuming, hence cost intensive. UV photolithography is suitable for mass production but need design and production of different masks for different waveguide patterns before they can be fabricated. In general, one of the techniques discussed here in the section or a combination of these techniques may be required for the fabrication of polymer waveguides.

1.3.1Deposition and Etching

The deposition method is often used to lay down a layer of light-guiding or cladding material on a substrate. For polymer waveguides, spin-coating and dip coating are two methods used to deposit a uniform layer on a substrate. Following deposition of light-guiding layer, techniques such as photolithography and other direct-write methods are used to define the optical pathways (Hikita 1993) (Wang 1994) (Hikitaa 1998). Suitable polymers (usually in powder form) are first dissolved in a suitable solvent before being spun on a substrate in the case of spin-coating. In the case of dip coating, the substrate is dipped into the solvent and then lifted off. After the deposition of the film on the substrate, the coated film is thermally treated to remove the excess solvent and to enhance the adhesiveness of the film to the substrate. Both spin-coating and dip-coating techniques are widely used to deposit thin films of polymeric materials on a substrate (Nishihara 1985) (Madou 2002). Vapor deposition (chemically or thermally) and sputtering are other thin-film deposition techniques popular in microelectronics industry but are not economical compared to techniques employed commonly for polymer material deposition.

The chemical wet etching processes use liquid-phase etchants. The wafer is immersed in a bath of etchant, which must be agitated to achieve good process control. The photographic developer used for photoresist resembles wet etching. Modern VLSI processes avoid wet etching to prevent the disposal of large amounts of toxic waste. For these reasons, they are seldom used in state-of-the-art processes, and use plasma etching instead. Plasma etching is a physio-chemical etching process in which the material is removed from the surface by means of bombardment of ions excited by a plasma (e.g. reactive ion etching). Ions of the reactive element are created in the plasma and an electric field is then used to direct the ions towards the areas to be etched. The optical pathways can be defined by using a mask with conventional photolithography that inhibits the etching. The advantage of reactive ion etching (RIE) is that the process can be used with almost any polymer material (Nguyen 2002). To ensure good quality of waveguide patterns, optimum control over critical etch parameters is required. The etch parameters influence the etching rate and the smoothness of the etched sidewalls. The critical parameters in the etch process are the pressure in the etching chamber, the gas flow of the etching gas and the radio frequency (RF) power of the plasma etching machine. O_2 is generally used as etching gas and different metal layers like chromium, aluminium or gold can serve as etch mask.

1.3.2 Direct UV Photolithography

Photolithography is one of the most widely used forms of lithography in micro-electronics industry. Making a choice of suitable low-loss polymer for fabrication of micro-optical components can exploit the same production line already available with the semiconductor industry. The direct UV photolithographic fabrication of optical waveguides, involves film deposition by spin-coating techniques, pattern transfer using lithography, and wet-chemical etching of resist film. Pattern transfer onto the photoresist is achieved by the use of contact masks as discussed in section 3.2. There are two types of photoresists: positive and negative. For negative photoresist, the exposed area remains after development while for a positive photoresist, the exposed area is removed after development.

The wavelengths of the light source ranges from deep ultraviolet (DUV) - i.e. 150 - 300 nm to near UV - i.e. 350 - 500 nm (Madou 2002). In the latter case, the g-line (436 nm) or the i- line (365 nm) of a mercury lamp is used. The sample is exposed to an appropriate dose of UV radiation under a UV lamp through a photomask. Photolithographic process offers very high contrast response allowing the definition of polymer waveguide features with dimensions ranging from few microns to few millimetres with a high degree of accuracy using precise controls. Essentially, photolithography is a two-dimensional process. However, three-dimension polymer waveguides have also been reported by using combined photolithography and reactive ion etching (Garner 1999).

1.3.3Casting/Molding/Embossing

Casting, molding, hot/cold embossing are few other techniques to fabricate polymer waveguides (Becker 2008) (Mohr 2004). There is a distinct advantage of using polymers over other conventional photonic materials such as glass and semiconductors for fabrication because high throughput techniques are available to the former (Eldada 2000). The tool used comprises of an inverted replica of the structure to be fabricated (i.e. a channel on the tool will become a ridge on the substrate, or vice versa). Waveguides are formed by subsequently either filling the channels or overcladding the ribs formed in the embossing process. In the case for casting or cold embossing, photochemically reactive polymers are required and a UV transparent substrate or a UV-transparent tool is required for processing.

One widely used technique in polymer micro-fabrication is hot embossing. The popularity of this technique can be partially attributed to its simplicity in tool and process setup as compared with other competing techniques, such as micro injection molding (Wiesmann 1996) (Chuang 2005). Embossed polymer devices and systems have demonstrated a great commercial potential, especially for biomedical, telecommunication and optical applications. However, embossing is subjected to some inherent process flaws limiting its capability. One major drawback is caused by the need of keeping the whole polymer material mass in thermal cycling, resulting in a long cycle time. The long dwell time at elevated temperatures could further result in degradation of the embossing polymer. Another drawback lies in the difficulty in reaching high embossing pressure and thus in replicating high aspect ratio features, because by nature hot embossing is an open-die compression melding process.

1.3.4 Direct-Write Techniques

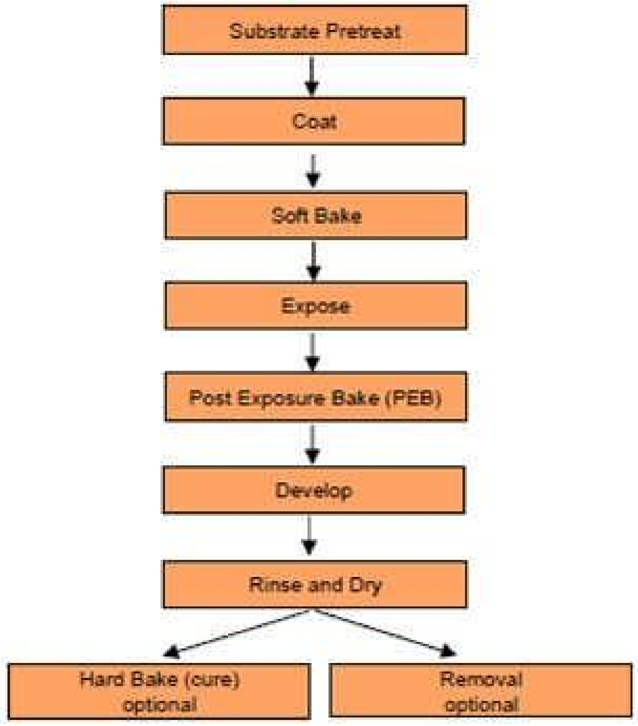
Direct-write lithographic techniques have the advantage of being maskless; thus capable of inexpensive rapid prototyping. However, compared with masked lithography, direct-write techniques can never compete with them in terms of manufacturing throughput. There are several direct-write techniques for the fabrication of optical waveguides. These include electron beam lithography, laser beam direct-writing and proton beam writing.

Electron beam lithography (EBL) technique is inspired from early scanning electron microscopes (Madou 2002). Essentially, it is based on the scanning a beam of electrons across a surface covered with a resist film sensitive to those electrons, thus depositing energy in the desired pattern in the resist film. One of the main advantages of EBL technique is high resolution. However, electrons undergo large angle scattering in a material. Due to the scattering of the electron beam inside the resist and substrate, and backscattering from the substrate, proximity effects are created, resulting in the exposure of the resist up to several microns from the point of impact (Mohammad 2004). This effect can be reduced by either using a thin resist layer and thin substrate support or by using lithography simulation software to optimize the design. Hence, EBL is essentially a surface micromachining technique. Nonetheless, it is capable of sub-10 nm for isolated structures and 30 nm pitch for dense periodic arrays of SiO2 pillars (Vieu 2000). EBL has been used to fabricate polymeroptical waveguides (Wong 2001) (Nakayama 1997) as well as channel waveguides in silica (Madden 1990) (Blanco 2001).

1.4 Fabrication Process

In this section, the steps of fabrication process of polymer optical waveguides fabricated and developed in this work are discussed. The organic polymer, SU-8 2002 from MicroChem, USA is the material for the core region in the fabrication of channel waveguides. An economical fabrication method was used to fabricate polymeric optical waveguides on (<100>) silicon wafers. NOA 61 is used as under and over cladding layer. The processing steps required for the fabrication of single mode optical waveguides are presented. To produce acceptable waveguides, the fabrication environment must be taken into consideration. Dust particles on the sample during fabrication lead to adhesion issues and can give problems during photolithography stages while transferring waveguide patterns using a contact mask. For compact device lengths, contamination must be more tightly controlled. Protecting wafers from particles becomes important to ensure good quality opticalwaveguides and devices. Therefore, a clean room conditions and practices are critical. The entire studies on waveguide fabrication was carried out in the fabrication facility available in the Semiconductor Devices Fabrication (SDF) Facility of CSIR-CEERI, Pilani.

Figure 3.5. Process description for NANO™ SU-8 2000 Series



The NANO™ SU-8 2000 Series are UV-sensitive photopolymers that have been developed for use in microelectronics applications (Microchem 2000). The SU-8 2002 was chosen as the raw material for waveguide fabrication because it follows simple fabrication steps. The SU-8 2002 inherently simplifies the steps of fabrication process and requirement of critical/complex equipment's for patterning waveguides is avoided. Fabrication of single mode SU-8 optical waveguides is based on a simple direct UV photolithography process (Tung 2005) (Pelletier 2006) (Yang 2009). Waveguide patterns can be developed simply by direct UV exposure through a photomask containing the pattern using economicallyaffordable equipments. The fabrication process flow chart (Microchem 2000) is shown in Fig. 3.5.

1.4.1Material Storage

The photoresist SU-8 and Norland optical adhesive is stored in a refrigerator away from the sunlight between 5°C to 20°C as per their material safety datasheets provided by the manufacturers of both products. SU-8 and NOA 61, both need to be equilibrated to room temperature before use.

1.4.2 Substrate Preparation

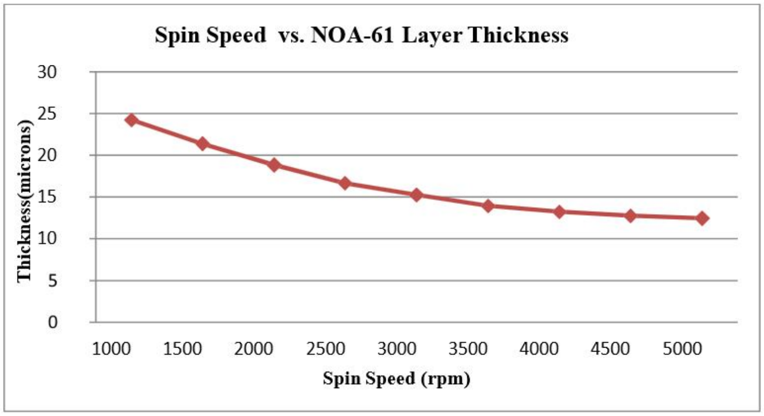
Silicon wafer was chosen as the substrate material in the polymer based optical waveguide fabrication. Silicon has a good surface quality and a refractive index of 3.48 at 1550nm. The surface preparation of the substrate is extremely important to ensure proper adhesion of the coated film. Typical contamination agents are dust and dirt from shipping or storage, and sample holder or finger prints from handling (Bach 1997). Substrates were ensured free of scratches and pits, clean and dry prior to use. If a light-guiding film is deposited on a scratched or cracked surface, the evanescent wave associated with the light would scatter from the damaged area, as a result the guide will be very lossy (Tamir 1975). The substrate wafers were prepared by piranha etch (H_2SO_4 + H_2O_2) whenever required before rinsing them with de-ionized water in an ultrasonic cleaner for 5 minutes. After that, they were rinsed with ethanol and dried with high pressure nitrogen gun. The cleaned wafers were dehydrated before use at 120-140°C in an oven. Thoroughly dehydrated wafers were critical in providing good adhesion between NOA 61 layer and Silicon wafer surface.

1.4.3Adhesive Film (Under-Cladding Layer) Deposition

There are a few techniques for film deposition in the waveguide fabrications. They are spin coating, dip coating, thermal vapor deposition, sputtering, chemical vapor deposition (CVD) and polymerization (Nishihara 1985). The Adhesive NOA 61 can be coated on Si-substrate directly without the requirement for any bulky and extremely expensive deposition chamber. The spin coating technique is the simplest and least expensive, but contamination and uniformity of the film needs control and check (Nishihara 1985). Adhesion of NOA 61 layersto the Si-substrate and core layer are critical issues in thin film fabrication processes. NOA 61 films were spun onto the substrate directly without any adhesion promoter. To obtain a uniformly coated film, formation of air-bubbles were prevented when dispensing the polymer with a syringe or a dropper. The volume of solution dispensed was kept constant for each sample to ensure the uniformity. The spin speed used to deposit the adhesive layer varied according to the final film thickness desired. Spin coater Model PWM-32 PS-R790 SS from Headway Research Inc., USA shown in Fig. 3.6 was used for coating the adhesive. Fig. 3.7 shows the NOA 61 film thickness after UV curing, and final thicknesses obtained after a series of experiments done for the same. A small amount of adhesive depending on the Si- wafer size was dispensed statically at the centre of the wafer in order to spread out the adhesive evenly from the center of the substrate. An under-clad thickness of more than 10 μm over silicon-wafer is required to achieve guidance of light through the SU-8 core as analyzed over a EIM 2D mode solver (Hammer 2012). A typical spin-curve for NOA61 is shown in Fig. 3.7. The spinning speed was kept at 4000 rpm for 30 seconds to achieve the pre-cure thickness above 10 μm as shown in Fig. 3.7.

Figure 3.6. Spin coating unit at CSIR-CEERI, Pilani

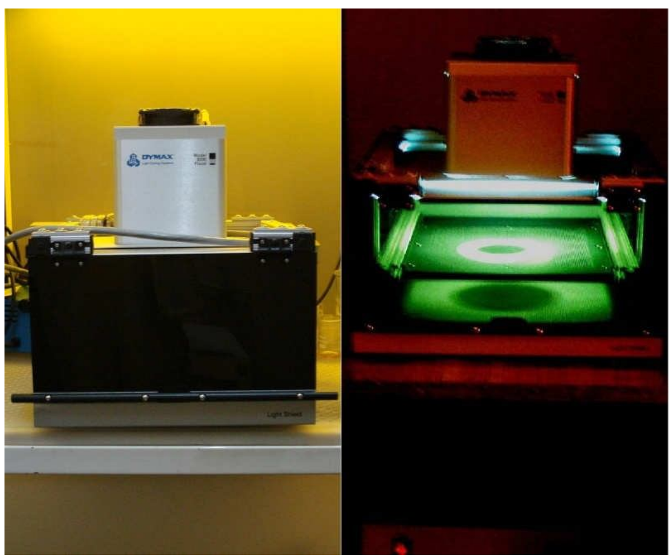
Figure 3.7. Spin Speed vs. Thickness Curve for NOA 61



1.4.4UV Cure

The Adhesive NOA 61 gets cross-linked when cured by ultra-violet light. The curing was carried out for 10 minutes at an average intensity of 48 mW cm-2 by using a high wattage (400 W) UV lamp (Dymax 5000EC) shown in Fig. 3.8, then left for stabilization at 60°C for next 15 hours. Besides improving adhesion between NOA 61 and Si-wafer, UV curing develops strong adhesion between NOA 61 and SU-8 2002 core layer to be coated over it.

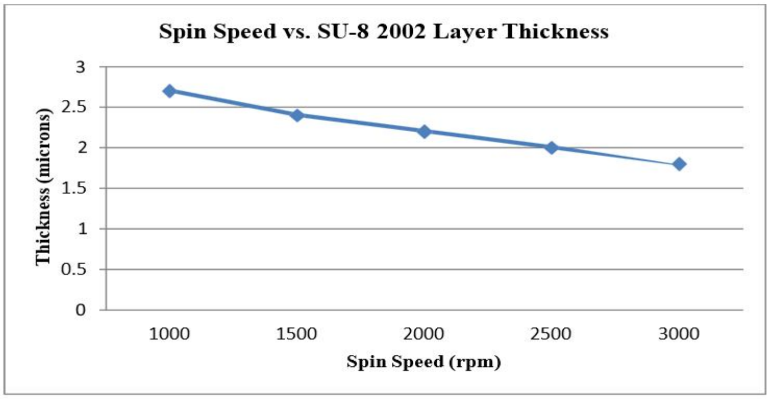
Figure 3.8. Dymax 5000 EC: Set-up (in left), during curing process (in right)



1.4.5Core (SU-8 2002) Layer Deposition:

The most important step in the waveguide fabrication is the light-guiding film deposition, in which a material of slightly higher refractive index is deposited as a thin film on a under- cladding layer of low-refractive index. The SU-8 2002 core material was spun at 1400 rpm for 30 seconds on top of NOA 61 coated Si-wafer, after equilibrating the wafer to room temperature, to achieve a thickness of around 2.5 μm. The thickness of the film deposited decreases in post-spinning baking process. The post-baking thickness of the SU-8 resist was verified by a stylus profiler discussed in section 4.3. Fig. 3.9 shows a typical spin curve for SU-8 2002.

Figure 3.9. Spin Speed vs Thickness Curve for SU-8 2002



1.4.6Pre-Exposure Soft Bake

After spin coating, the films were soft-baked using a two-step process for a small duration of time to remove the solvent from the film. The specific time and temperature are dependent on the composition of the substrate as well as the thickness of the film. For SU-8 2002-layer, specification sheet of SU-8 2000 series supplied by manufacturer suggested two-step soft- bake for a duration of 1-2 minutes, first at 60 ºC then at 95 ºC. Pre-exposure bake was done on a hot plate in conjunction with a post-exposure or pre-develop bake. The soft-bake was carried out immediately after spin coating. The uniformity of the film may get altered atplaces due to presence of solvent in a fresh-coated film when moved from spin-coater to hot- plate. Therefore, adequate care was taken to keep the substrate in a horizontal position to avoid any change in level while transferring the substrate from spin coater to hotplate during the soft-bake process. The temperature and the duration of soft-bake determine the residual solvent concentration in SU-8 at the moment of UV exposure. For small durations less than 5 min, poor resolution and bad definition of sidewalls was observed while for long durations greater than 1-hour, insufficient cross-linking occurs due to partial development of SU-8 (Keller 2008). Here, a two step-process (65 °C for 5 min and 95 °C for 20 min) was used to remove any traces of solvent before exposure.

1.4.7UV Photolithography

Photolithography process involves the transference of two-dimensional patterns available on the mask to the polymer film. After being developed, the film has an exact replica of the mask patterns. After the soft bake, the wafers were allowed to cool to room temperature before photolithography. Once the mask and the wafers were appropriately aligned, the exposure process was carried out. The alignment was done keeping in mind that the end- facets of the devices will be prepared by cleaving of the wafers. In order to achieve a better resolution of the image, the mask was placed in physical contact with the wafer also known as hard contact or contact exposure. Unfortunately, physical contact with wafer degrades the mask faster unlike non-contact, and proximity masks, which are few microns above the wafer. The latter method prolongs the mask lifetime but degrades the resolution of the resulting pattern since the separation causes a shadowing effect that increases as the light incidence is less normal. The hard contact method also degrades the uniformity of the film, as the polymer will stick to the mask, in case the film is not fully dried after the pre-exposure soft bake. However, hard contact method was used to ensure better resolution for the patterned waveguides as it was critical to achieve better device performance, as will be discussed in chapter 4. The amount of incident radiation required for an optimum resolution depends on several parameters such as the coating thickness, underlying surface reflectivity, structure size, desired wall profile and also feature uniformity (Gang 2004). SU-8 waveguides were realized by UV exposure for 90 seconds in contact with photomask using aKarl Suss MA56 mask aligner, shown in Fig. 3.10, with an i-line mercury lamp providing intensity ~10 mW cm^{-2}.

Figure 3.10. Karl Suss MA56 Mask Aligner at CSIR-CEERI, Pilani

1.4.8Post-Exposure Bake

After exposure, a post exposure bake ≥ 90 C is required to cross link the resist. The issue with thin SU-8 films is that this results in cracking or delamination mainly due to thermal stress. One way to overcome the issue is to use high exposure dose as it corresponds to a higher photo-acid concentration and improves cross-linking. For a post exposure bake ≥ 60 ºC, the thickness of the SU-8 layer stays uniform while the tensile stress increases linearly. However, the absolute stress values are considerably low at higher exposure doses. Theduration of post exposure bake has only minor influence on the film thickness and stress (Keller 2008). However, high exposure dose has a negative influence on the lithographic resolution. High exposure dose leads to waveguide broadening and a reduced trench width due to optical effects such as diffraction at the mask and reflection on the substrate (Zhang 2004). A post exposure two-step baking process (65 ºC for 2 min and 95 ºC for 5 min) is used to crosslink the polymer.

1.4.9 Waveguides Development

Once the photolithographic process is done followed by a post exposure baking, the next step is selective removal of the film from unexposed areas of the samples with the etching processes.U-8 2002 can be developed by wet-etching method, which can be done without costly and bulky equipments such as RIE, ICP or plasma etching. By wet etching, it is understood that the elimination of a material is accomplished by its dissolution in an adequate etching solution. It is mainly used for cleaning, shaping and polishing. The drawback of wet chemical etching is the lower quality of sidewall resolution of the waveguides. The wafer was placed in a bowl filled with SU-8 developer, the etching solution: Propylene Glycol Methyl Ether Acetate (PGMEA). Sufficient amount of developer was used to completely immerse the wafer. The wafer was allowed to rest in developer for a pre-determined length of time to allow dissolution of the unexposed areas. The develop time was set as 70 seconds and then rinsed in IPA for 10-15 seconds. Following the rinse, the wafer was blown dry (N2) to remove the developer solvent and dry the wafer. The waveguide patterns if loosely adhere to the under-clad layer, will get displaced indicating poor adhesion between core and cladding material.

1.4.10 Adhesive Film (Over-Cladding Layer) Deposition:

Coating of NOA 61 layer as over-clad is the final step of waveguide fabrication process. The over-clad deposition is done following the same steps as for the under-clad layer deposition. Following the photolithographic and chemical wet-etching process, an over-cladding layerwas deposited and the layer was UV-cured. The process of deposition of under-clad layer was repeated here to deposit over-cladding layer over the SU-8 waveguides. The fabricated 1× 4 device is shown in Fig. 3.11. A 1 × 4 device after over-clad deposition is not shown here due to poor visibility of features of waveguide patterns through over-clad layer. Finally, a hard bake at around 120-140 ºC for 60 to 120 minutes is suggested to remove further any traces of solvent or developer left behind. The whole fabrication process (from section 3.4.1 to 3.4.10) is summarized in Fig. 3.12 before concluding this chapter.

Figure 3.11. Fabricated Conventional 1 × 4 splitter

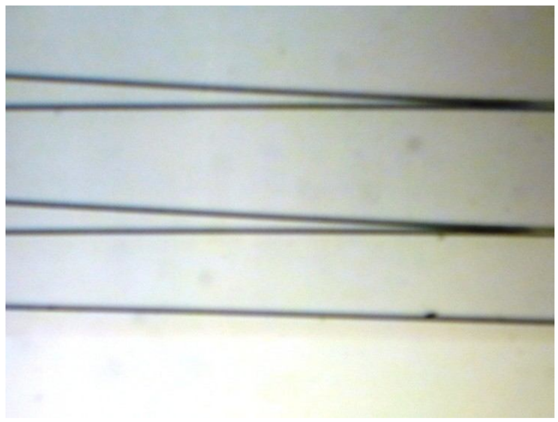
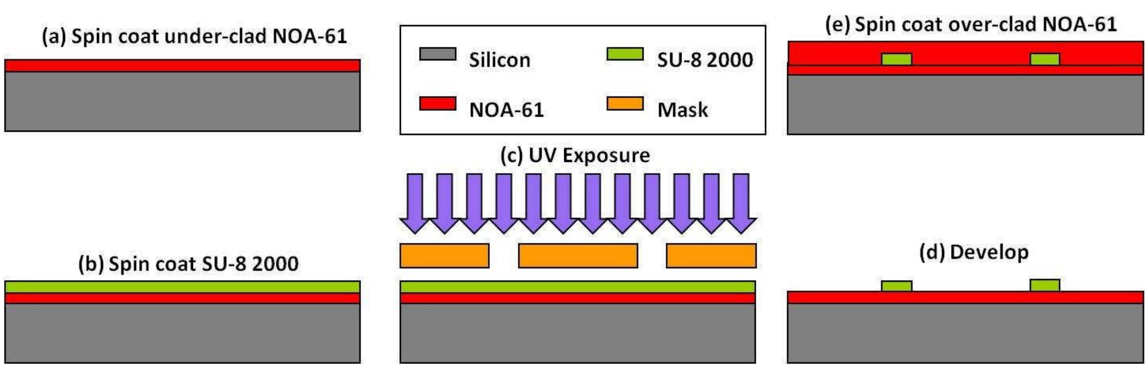


Figure 3.12. Polymer Waveguide Fabrication Process Steps



1.5 CONCLUSION

The design and fabrication of Y-branch waveguide which is the basis of the optical power splitter was discussed in the chapter. The conventional Y-branch design for 1 × 4 power splitter was presented in the chapter. The design of mask for fabrication of 1 × N splitters using L-Edit (Tanner Tools) was presented here. An overview of the micro-fabrication procedures and techniques for polymer waveguides was presented in the chapter. Finally the steps of fabrication process used and related issues observed were discussed in the chapter. The substrate surface is coated with NOA 61, followed by UV curing and baking and then left for stabilization at 60ºC for 15 h. The SU-8 2002 core material was spun on top of NOA 61 coated silicon substrate and then soft baked using a two-step process to remove any traces of solvent after exposure. Channel waveguide width of 2.5 μm was realized by UV exposure in contact with a photomask. A post-exposure two-step baking process was used to crosslink the polymer. The photoresist-coated UV-exposed substrate was developed in PGMEA and then rinsed in IPA. An over-clad of NOA 61 was coated on developed SU-8 waveguides. Finally, a hard bake at 140 C for 1 hour, removed the traces of developer or solvent left behind.

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