Chapter 2

Integrated Optics

This chapter provides a brief review on Integrated Optics covering the history of the technology until its current developments. Emphasis will be placed on the Planar Lightwave Circuit made of silica thick film, which is the type of sample used throughout this project.

2.1: History

At the end of 1969, S. E. Miller from Bells Lab has introduced the Integrated Optics (IO) [1], from the inspiration of Integrated Electronics. The urge of having miniature size of optical devices with multiple optical functions [2] is driving the span of integrated optics. Additionally, rapid development of internet services require overwhelming high data transmission rate during the end of 20th century had expedite the growth of integrated optics [3]. As the name suggests, Integrated Optics is a technology intended to build and integrate multiple individual optical components on a common planar substrate [4, 5]; IO is also known as Planar Lightwave Circuit (PLC). Some may interpret it as a thin film optical to which be able to perform complex optical functions [4, 6]. Introduction and rapid progression of Integrated Optics can be said as a new circle of life with the matured fabrication technology. Hitherto, the progress in technology enables optical devices with low loss; high stability towards thermal and environmental can be produced at a relatively low cost. Thus, to produce success integration circuit; which involves materials for characterization; it is really relates with thermal expansion of coefficient and refractive index. Integrated optics is getting the limelight from the world as its deployment in optical communications, homeland security, forensics and medical. Hence, continuous growth and deployment of IO shows that this technology has bring a tidal wave which constructively improves our lives and inviting a revolutionary in industry.

Other underlying motivation to fuel the growths of integrated optics is the high frequency operability that could not be done by its counterpart, microelectronics [3, 7]. This operational region is in the Terabits per second region, corresponding to the current optical communications networking transmission window. Due to this outstanding characteristic, Passive Optical Network (PON) has utilized planar lightwave circuits. Recently, researchers from Intel had found a way to fabricate the first 40GHz silicon laser modulator in the world which marks the rise of Tera-computing era [8].

As mentioned earlier, PLC has been widely deployed in the current optical networking progression, where optical signal manipulation has become one of the great interests to ensure reliable networking. Such a task may cover the simplest role such as signal guiding and splitting to a complicated one like signal encryption for security purposes. Even though some task can be performed by optical fibers, it is more convenient to have a single optical device which is able to perform more functions than a fiber. Competency of integrated optics to provide multiple optical functions on a common platform is therefore a route for us to achieve high speed computing era [9].

The innovation in microelectronics technology gives high performance optical devices can easily be fabricated. Yet, due to tight tolerance on optical signal coupling, end optical device products are sell at high pricing. Well trained personnel are required to perform pigtailing procedure, and yet the throughput is not credible in the economical aspect.

For smooth growth of Integrated Optics, there is a tight relationship between the optical component material and the substrate. Concerns take into account for materials selection are refractive index, thermal expansion coefficient, propagation loss and the availability of fabrication techniques. Among available optical materials, silica is found to be a suitable candidate for the Planar Lightwave Circuit or sometimes refer as planar waveguide fabrication, as it shares similar index profile from silica optical fiber. The index matched profile says the signal loss resulted from refractive index mismatch is keep at minimal level. In addition, cross-over of fiber fabrication technology and microelectronics fabrication technology [10] has popularized silica. Silica planar waveguide will be the focus of the next section of this dissertation since the in-house fabrication facility is meant for silica planar waveguide. Table 2.1 summarizes the available fabrication technique corresponding with different optical materials.

Table 2.1: Commonly used waveguide materials and the corresponding fabrication techniques [4]

Material	**Fabrication**	**Advantages**	**Application**
$LiNbO_3$	Metallic diffusion, proton exchange	Enhanced light manipulation, anisotropic	Modulators, Switches
Polymers	Spin, dip coating	High versatility	Sensors, Modulators
SiO_2: Si	Thermal oxidation, Flame Hydrolysis Deposition (FHD), Chemical Vapor Deposition (CVD)	Microelectronics technology compatible	Passive devices
Semiconductors	Epitaxial growth	High level of integration	Amplifier, Laser

2.2: A Brief Review on Silica Waveguide Fabrication

Integrated optics has offered an alternative route to produce optical components, channel waveguides, with high device stability and suitability for the integration compared to conventional bulk- and fiber-optics [10]. Silica has become a choice of material since Nippon Telegraph and Telephone (NTT) developed a technique called Flame Hydrolysis Deposition (FHD) for silica deposition out of optical fiber fabrication technology and LSI micro-fabrication technology [3, 10]. Bridging between the two technologies enables silica film to be deposited on silicon crystal substrate and hence integration of passive and active components can be realized.

Deposition of silica is done on silicon wafer and sometimes quartz wafer. As the geometry of these substrates is planar, the deposited waveguide hence follows the substrate's geometry. Also, planar geometry enables more optical circuitry design in micrometers scale to be fitted; in other words, dozens of optical devices can be produced from a piece of wafer and hence becomes cost effective. Another advantage of having planar form devices will be the incorporation of active and passive component on a circuitry design which cannot be done by optical fiber. Such incorporation has positive impact towards Passive Optical Network (PON) since the incorporation is able to perform multi-threading process covers from signal amplification, signal splitting, and signal processing [11].

Aside from the deposition technology by NTT, other deposition methods such as Plasma Enhanced Chemical Vapor Deposition (PECVD), Pulsed Laser Deposition (PLD) [10-14] have been extensively studied by others. Though their names are different, they share a similar approach of the state of material to be deposited using suitable method which can be transferred onto substrate using deposition technique. Sometimes, substrates are heated up for better adhesion purpose. Table 2.2 shows some of the available material deposition methods corresponding to the deposited material.

Table 2.2: Available deposition technologies.

Process	**Materials**	**References**
Flame Hydrolysis Deposition (FHD)	SiO_2-TiO_2 SiO_2-GeO_2	[10, 12]
Chemical Vapor Deposition (CVD)	SiO_2-P_2O_5	[10, 12]
Vapor Deposition (VD)	SiO_2-TiO_2	[10]
Ion exchange	Multi-components glasses	[10, 13]
Pulsed Laser Deposition (PLD)	Germanate glass	[12, 13]
Sputtering	Silica	[12, 13]

Optical circuitry is then transferred to the deposited films by photolithography, Ion Exchange or via laser writing technique. The former methods may be the conventional large scale integration (LSI) UV-photolithography or proton beam technique [15]. The recent laser writing method is a relatively new. UV-laser and femto-second laser are the common applied laser source under this technology. Further etching procedure is required for those sample which has experienced in photolithography. As soon as the circuit has been imprinted, they are coated with a layer of low refractive index silica for protection and signal confinement within developed core. Finally, characterization of the samples, including loss measurements of diced and polished waveguide will be performed. Fig. 2.1 shows the process flow of the aforementioned waveguide production.

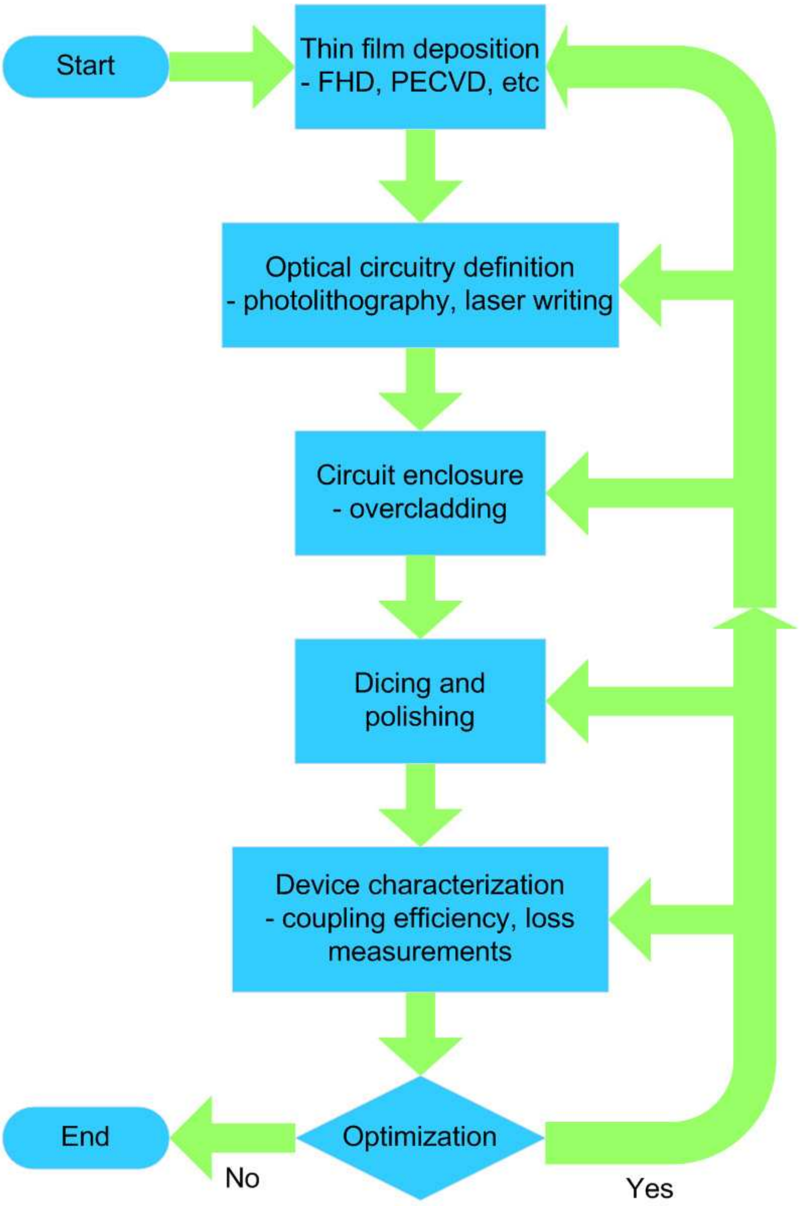

Fig. 2.1: Planar waveguide fabrication process flow

2.2.1: Silica Deposition via Flame Hydrolysis

Deposition of silica on planar substrates via flame hydrolysis reaction has been widely used in photonics for decades when it was initially invented for fiber performs by NTT. The technique manages to produce low loss SiO_2-TiO_2 planar waveguides with about 0.1dB/cm of propagation loss [16]. Flame hydrolysis deposition shares the operating principle with Vapor Axial Deposition (VAD) where Silicon Tetrachloride ($SiCl_4$) vapor is injected into Oxy-Hydrogen flame to form silica particles called soot. Incorporation of dopants vapor such as Germanium Tetrachloride ($GeCl_4$) and Phosphorus Oxychloride ($POCl_3$) to tailor the desired silica properties by varying the composition ratio of the involved reagent is also possible. For the FHD process, instead of depositing the soot film onto cylindrical substrate, soot layer is deposited on silicon planar substrates and both of the processes are depicted in Fig. 2.2a and 2.2b respectively.

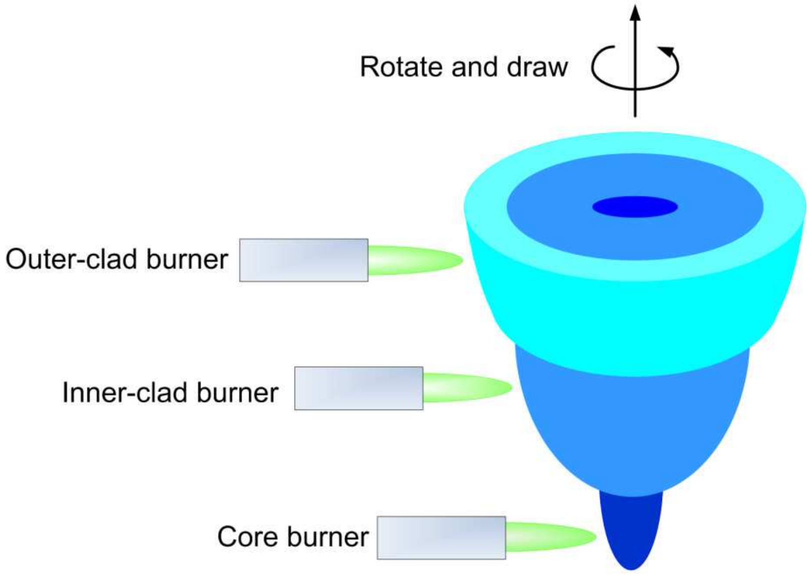

Fig. 2.2a: Schematic process of VAD [13]

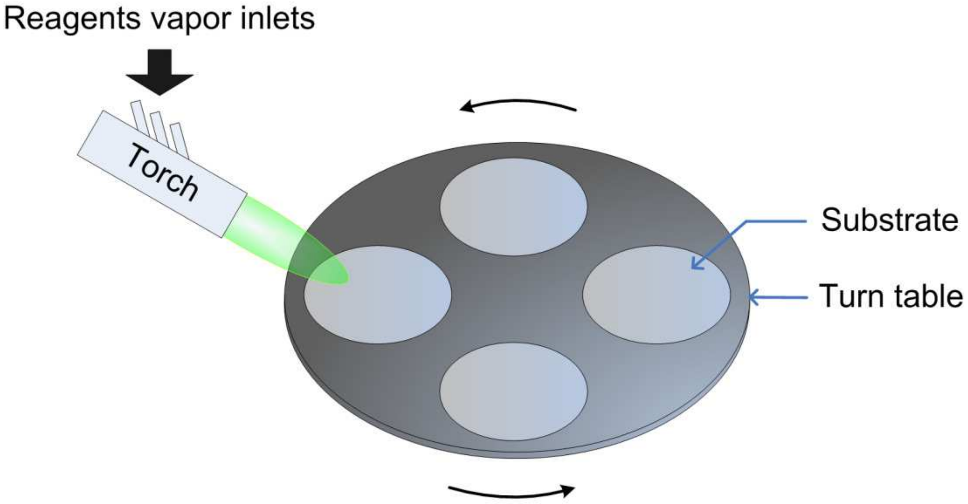

Fig. 2.2b: Schematic process of FHD [13]

The deposited soot layer is porous and can easily be peel off from the substrate. Consolidation of the soot layer at elevated temperatures is then required to produce rigid and dense glass from the soot. Throughout the deposition process, the substrate is heated up at temperature of about 240˚C to prevent water molecules from flame process being absorbed by the hygroscopic soot layer [13]. For any type of deposition techniques used, substrate selection has significant role on waveguide/device functionality. Silicon and fused silica wafers are the commonly used substrate in film deposition. For silica deposited on silicon wafer waveguide, due to the incompatibility in thermal expansion coefficient between the two materials, the level of birefringence exhibited is higher to that of silica deposited on quartz wafers. This occurrence is useful when waveguide with polarization dependency is required. Due to the compatibility with integrated electronics and the wide availability, silicon has been widely used as the substrate for planar waveguide fabrication. Table 2.3 summarizes some of the material properties of the silicon and fused silica wafer.

Table 2.3: Material characteristic of silicon and fused silica [10]

Property	**Silicon, Si**	**Fused silica, SiO_2**
Refractive index, n	3.5	1.445
Transmission wavelength, λ (μm)	1.2-10	0.12-4.5
Thermal conductivity, κ (W/cm deg)	1.6	0.014
Thermal expansion coefficient, $\alpha(10^{-6}/\text{deg})$	2.5	0.35
Young's modulus, $E(10^4 kg/mm^2)$	1.1	0.78

Through the precise control on the flow rate or the compositional ratio of the involved reactants, uniformity and thickness of deposited film can be tailored easily. Introduction of halide reagents into the highly reactive flame causes oxidation and perhaps hydrolysis on the substances to be occurred where these processes are shown below respectively:

$$SiCl_4 + O_2 = SiO_2 + 2Cl_2 \qquad \text{(Eqn.2.1)}$$

$$SiCl_4 + 2H_2O = SiO_2 + HCl \qquad \text{(Eqn.2.2)}$$

Appearance of such chemical processes enable the creation of soot particles and hence the deposition. The expansion of soot layer deposition is mainly controlled by the coalition and aggregation of existing particles within the flame [13]. In general, deposition process is a process where a large population of oxides from nucleation process undergoes coagulation and being transferred to the substrate to form the porous soot layer.

Annealing process is applied to the porous soot layer before it is ready for any channel development. Soot layer can be annealed to become a full consolidated glass or partially consolidated. The former is for direct channel development whereas the later is meant for additional doping process. Additional dopants such as Bismuth, Erbium and Ytterbium at a certain concentration can be doped into the partially sintered glass network via solution doping or spray doping method to provide the signal amplification functionality. Apart from the passive function, doped silica waveguides can be transformed into waveguides with active functions. Once the doping process is over, those doped samples will be heated up again to achieve full consolidate glass. A summary of the silica film deposition is shown in the Fig 2. 3.

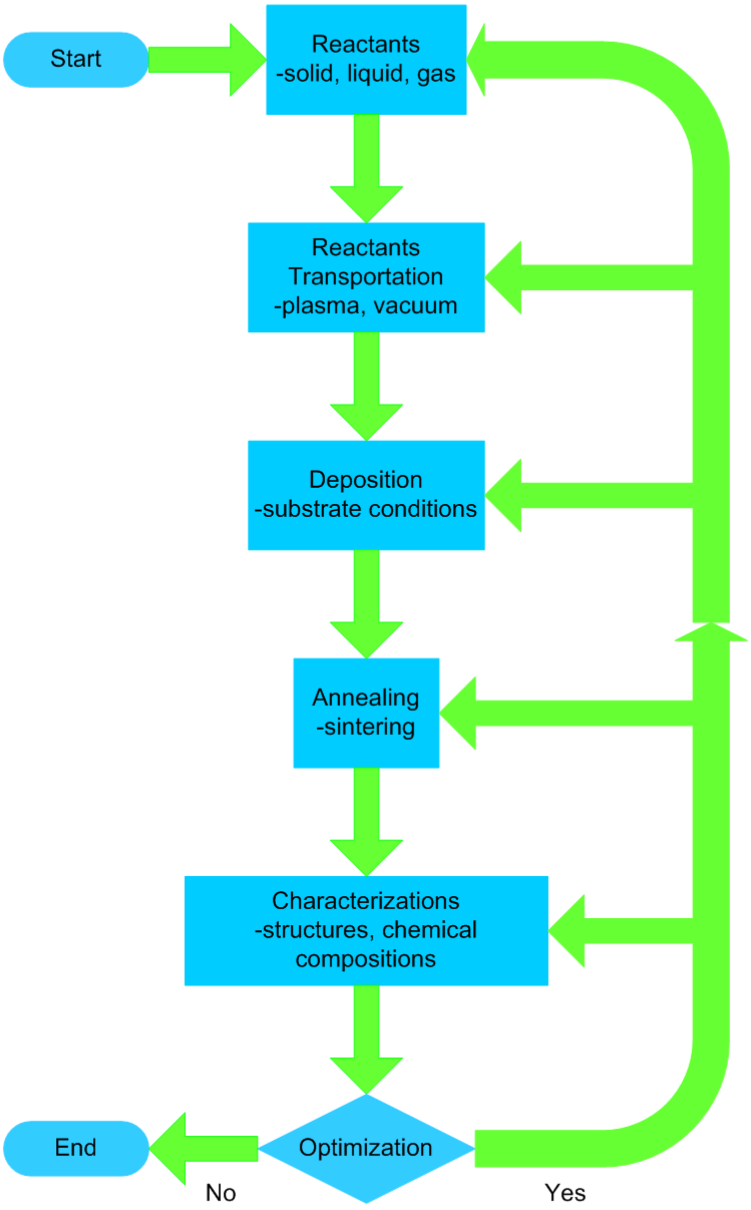

Fig. 2.3: Silica film deposition process flow

2.2.2: Optical Circuitry Definitions via Photo-Lithography

Combination of photolithography and dry etching has been used to fabricate optical channels within deposited glass layer. In photolithography, fabricated core layer is spin coated with a layer of ultra-violet (UV) sensitive chemical substance, photo-resist. A UV source is then illuminated through a photo-mask on the photo-resist. The photo-mask is a mask which contains a pre-designed optical circuitry, allows UV source pass through the circuitry and irradiate the uncovered photo-resist region subsequently. Waveguide structure will be formed along the UV exposed area which is a product from the chemical reaction between photo-resist and UV irradiation. Unexposed photo-resist part is then washed off, leaving only the exposed part. In order to obtain the waveguide structure whichever covered by the UV exposed photo-resist layer, Reactive Ion Etching (RIE) is applied to etch away the unprotected core layer. The sample is then further processed to remove the remaining photo-resist layer. Glass deposition process in then initiated again to deposit lower index glass, over-cladding, above the developed channel. The serial of the this process is shown in Fig. 2.4

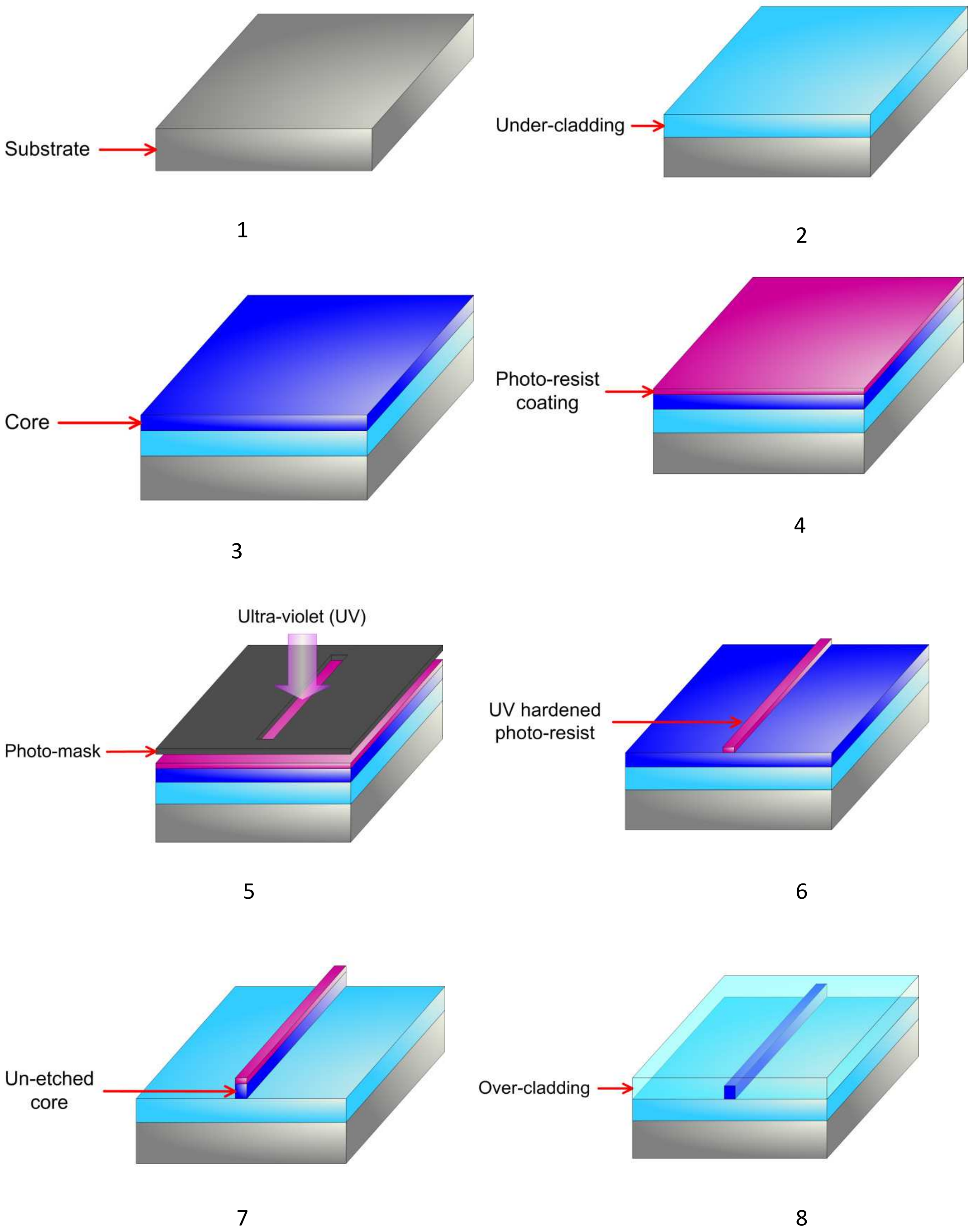

Fig. 2.4: Formation of single channel buried waveguide via combination of photolithography and etching

2.3: Direct Laser Written Waveguide

Apart from using photo-lithography method to define optical circuit, exploitation of mature laser technology is another promising technique to fabricate optical channels in planar samples. Laser writing mechanism can be imagined as hand-drawing on a piece of paper using a pen where the pen acts as the laser and the waveguide is represented by the paper. Femto-second laser and UV laser are the available laser sources to accomplish the task [12, 17-19]. In direct laser writing methods, the applied principle is to induce refractive index change on the photosensitive material through UV irradiation while ultra-fast laser utilizes non-linear absorption of high intensity pulses for energy deposition to modify the atomic network and hence the optical properties of dielectrics [20, 21]. This non-linear effects in transparent materials enables the laser to be focus precisely within a fraction of volume where later stimulate microstructure changes through densification, bond reconfiguration or defects formation process [20, 21]. For direct UV laser writing, the correspondence refractive index modification is associated with photosensitivity of elements such as Germanium (Ge) towards UV irradiation. Under UV irradiation, photosensitive elements will absorb incident UV energy and modify refractive index in the vicinity.

Comparatively, direct laser writing and conventional photolithography has their own advantages over each other. From the viewpoint of economics, the former method was able to produce devices in mass production and is a mature technology as it inherits the advantages from microelectronics. Whereas, the latter can be operated at normal environment and needs no high-end machines to produce desirable planar waveguide circuits compared to later technique, which lowers the maintenance cost significantly. Table 2.4 below summarizes the advantages and the drawbacks of both techniques.

Table 2.4: Advantages and disadvantages of photolithography and direct laser writing

Techniques	**Advantage**	**Disadvantage**
Photolithography	Mass production	Clean-room environment required
	Matured technology	High maintenance cost
		Not friendly for prototyping
Direct laser writing	Ease of sculpturing [12]	Low throughput
	Single step patterning process	Tight tolerance on alignment

2.4: Active and Passive Optical Device

Optical devices can be categorized into two in general: active and passive devices. Active optical device is a combination of waveguide structure with material processing gain and/or optical non-linearity function resulting active functionalities [22] such as opto-electric conversion and optical signal amplification [21, 23]. Development of these devices is significant after realization of laser by Basov et al and the effort studies on non-linear optical effects by Gibbs and Chemla [22]. Similar with laser, waveguides embedded with optical gain function is governed by the underlying physics of stimulated emission via external photon excitation. Undoubtedly, raise of active devices will once again impacts the current photonics world by offering complex optical processing functions.

On contrary, passive optical devices are defined as a optical waveguide which has no intelligence on complex signal manipulation [22]. In other words, these devices can only be used to guild and split optical signal without any further signal properties modifications [24, 25]. Fig. 2.5 shows a typical passive optical device which only possesses signal splitting function. In fact, optical gain exhibits in active optical devices also find its application in passive device by introducing wavelength multiplexing and optical filtering functions [22].

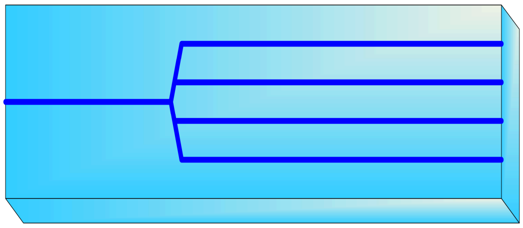

Fig. 2.5: Y-branch 1x4 power splitter used in current optical networking.

2.5: Summary

Some brief review on the waveguide fabrication technologies as well as the comparison has been discussed in this chapter. Conventional way of fabricating waveguides is an inheritance and modification of microelectronic's technology. Different combinations of techniques were strictly dependent on the type of materials used in production and plays significant role in device functionalities. Apart from traditional, deployments of laser technology and proton beam techniques are relatively new and available for consideration. However, they are likely to be used for rapid device prototyping purpose instead of mass production. Similarly with microelectronics, planar optical waveguides can be designed either to have active function or just plain passive function. Both of them are complementary to each other in the sense of optical functionality which can be foreseen from various sectors, the needs of data encryption and decryption in data communication at high speed says Tera-hertz (THz), for instance.

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