Silicon based IR filters

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SILICON BASED IR FILTERS

by

Prakash Mokashi

The design and fabrication of silicon based IR (Infrared) filters for high-speed optical communication systems are the topic of this thesis. Its novelty is in two aspects: 1) Use of silicon wafers as an optical guiding medium; 2) Use of wafer bonding technique to attach two optical elements together.

The structure consists of two optical waveguides, the bus waveguide and the drop channel waveguide. A ring on top of these waveguides couples them in such a way that only one narrow spectral line is removed from the bus waveguides which propagates in the drop-channel waveguide. The assembly is fabricated using wafer-bonding technique in silicon. A precise control over the waveguide dimensions, the ring dimensions and the distance between the ring and the waveguide is required for a specific spectral line to be coupled to the drop-channel waveguide. It is hoped that the use of VLSI technologies in fabricating optical elements may therefore advance the area of optical networking and sensing.
SILICON BASED IR FILTERS

by

Prakash Mokashi

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Master of Science in Computer Engineering

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CHAPTER 1
INTRODUCTION

1.1 Background

The increasing growth of the Internet and the consequent need for more and more bandwidth has given birth to the new technique called Wavelength Division Multiplexing (WDM). It represents the second major fiber-optic revolution in telecommunications, the first being when, major telecommunication companies replaced copper wires and microwave links with optical fibers. Taking advantage of WDM, long-distance carriers have been able to avoid laying expensive new cables by sending data using additional wavelengths through existing fibers.

Another important development that has occurred in recent years is the first commercial application of integrated-optical devices in analog and digital fiber-optic communication systems and networks. High-speed electro-optic intensity modulators and monolithically integrated electro-absorption modulators, for example, are widely used in long-distance terrestrial and submarine lightwave systems to encode the digital signals with little or no additional frequency-chirp into the optical carriers. Moreover, fast electrooptic polarization scramblers have become an important component in ultra-long transoceanic communication systems to eliminate anisotropic gain saturation in the optical amplifiers. In addition, optical wavelength multiplexers and demultiplexers using silica-based devices are employed in the multi-wavelength communication systems to combine and separate the various optical carriers at the transmitters and receivers. These applications are just the beginning of an even more widespread commercial use of
integrated-optical devices in future long-distance and local area networks. The design and manufacturing of integrated optical resonators are discussed. These optical resonators have come up to be the future of Wavelength Division Multiplexing.

1.2 Need for Resonators

The increasing interest in photonic integrated circuits and the increasing use of all optical fiber networks as backbones for global communication systems, has been based in large part on the extremely wide optical transmission bandwidth enabled by optical fibers and the large degree of transparency that they offer. This has accordingly led to an increased demand for the practical utilization of the full optical bandwidth available, which is presently limited by electronic systems. In order to increase the aggregate transmission bandwidth, it is generally preferred that the spacing of simultaneously transmitted optical data streams, or optical data channels on the same optical fiber be closely packed to accommodate a larger number of channels. In other words, the difference in wavelength between two adjacent channels needs to be minimized. Simply put, each channel is characterized by a central optical frequency (central wavelength). Nowadays, the spacing between two adjacent channels is 2 nm or 300 GHz. This bandwidth is much larger than the channel bandwidth; the fastest optical communication system is 10 Gb/sec or 5 GHz/sec.
Figure 1.1  Schematic of a Typical Add/Drop Multiplexer

Optical Waveguide Resonators that access one channel of a wavelength division multiplexed signal while leaving other channels undisturbed has become an essential component of photonic integrated circuits and optical communication systems. Among various devices studied recently, resonant filters are attractive candidates for channel dropping because they can potentially be used to select a single channel with a very narrow linewidth accuracy.
Figure 1.2  a) Schematic of Optical Resonator (top view)

b) Cross Section of Optical Resonator
1.3 Basic Optical Resonator

The schematic of a proposed optical resonator is shown in Fig. 1.1; two waveguides, the bus and the drop, are coupled through an optical resonator system. While WDM signals (i.e. multi-frequency signals) propagate inside one waveguide (the bus), a single frequency channel is transferred out of the bus and into the other waveguide (the drop) either in the forward or backward propagation direction, while completely prohibiting cross talk between the bus and the drop for all other frequencies. The performance of an Optical Waveguide Resonator is determined by the transfer efficiency between the two waveguides. Perfect efficiency corresponds to 100% transfer of the selected channel into either the forward or the backward direction in the drop, with no forward transmission or backward reflection into the bus.

In this project, a ring waveguide is used as a resonant filter. In such a geometry, the forward propagating wave in the bus excites a rotating mode in the ring, which in turn couples into the backward propagating mode in the drop. Ideally, at resonance, 100% transfer can be achieved. However, radiation losses and bending losses inside the ring have the effect of reducing the transfer efficiency. Furthermore, the ring waveguides may support multiple resonances, thus in principle may transmit multiple channels.

1.4 Brief Discussion about this Thesis

The discussion is mainly aimed at the design and fabrication aspects of silicon based IR filter using ring optical resonators. Chapter 2 of this thesis describes the basics of waveguides, different types of waveguides and different parameters of waveguides. Chapter 3 explains in detail the fabrication procedure for these optical resonators.
Chapter 4 gives an idea of the experiments that were carried out on the waveguides. Chapter 5 draws some conclusions from the experimental results. It also explains some future improvements that can be done in the design of these resonators. It also gives some applications for these resonators.
CHAPTER 2
INTRODUCTION TO WAVEGUIDES

2.1 Waveguide Structure

A waveguide restricts the three-dimensional "free space" propagation of the electromagnetic wave to a single dimension. Usually waveguides are:

- Low loss: That is, the wave travels along the guide without greatly attenuated as it propagates.
- Routable: This means that we can gently bend the guiding structure without losing contact with the wave, without generating reflections, and without incurring additional loss.
- Large spectral bandwidth

There are many different waveguide structures. Usually they are uniform in the direction of propagation of the guided wave, that is, one cannot tell where one is along the waveguide by physically looking around one.

A waveguide structure essentially consists of a core with a refractive index $n_1$ surrounded by a cladding of slightly lower refractive index $n_2$. The cladding supports the waveguide structure whilst also, when sufficiently thick, substantially reducing the radiation loss into the surrounding air. In essence, the light energy travels in both the core and the cladding allowing the associated fields to decay to a negligible value at the cladding air interface. Fig 2.1 shows the structure of a cubical waveguide.
In the following discussion, we discuss the different parameters of waveguides. The ray theory approach is used for specifying these parameters.

2.2.1 Total Internal Reflection

For studying the propagation of light within a waveguide using the wave theory, we need to consider the refractive index profile of the material. The refractive index of the medium is defined as the ratio of the velocity of light in vacuum to the velocity of light in the medium. When a ray is incident on the interface between two dielectrics of different refractive indices, refraction occurs. The ray approaching the interface is propagating in a dielectric of refractive index \( n_1 \) and at an angle \( \phi_1 \) to the normal at the surface of the interface. If the dielectric on the other side of the interface has a refractive index \( n_2 \) which is less than \( n_1 \), then the refraction is such that the ray path in the lower index medium is at
an angle $\phi_2$ to the normal, where $\phi_2$ is greater than $\phi_1$. The angle of incidence $\phi_2$ and $\phi_1$ are related to each other, and to the refractive indices of the dielectrics by Snell’s law of refraction, which states that:

$$n_1 \sin \phi_1 = n_2 \sin \phi_2$$  \hspace{1cm} (2.1)

**Figure 2.2** Basic Principles of Light Propagation

(a) Refraction  (b) the limiting case of refraction showing the critical ray at an angle $\phi_c$  (c) total internal reflection where $\phi > \phi_c$
A small amount of light is reflected back into the originating reflecting medium (partial internal reflection). As \( n_1 \) is greater than \( n_2 \), the angle of refraction is always greater than angle of incidence. Thus when the angle of refraction is \( 90^\circ \) and the refracted ray emerges parallel to the interface between the dielectrics, the angle of incidence must be less than \( 90^\circ \). This is the limiting case of refraction and this angle of incidence is known as the critical angle \( \phi_c \). The value of the critical angle is given by:

\[
\sin \phi_c = \frac{n_2}{n_1}
\]

(2.2)

At angle of incidence greater than the critical angle, the light is reflected back into the originating dielectric medium (total internal reflection) with high efficiency.

### 2.2.2 Acceptance Angle

Figure 2.3 illustrates a meridional ray \( A \) at the critical angle \( \phi_c \) within the waveguide at the core-cladding interface. It may be observed that the ray enters the waveguide core at an angle \( \theta_a \) to the waveguide axis and is refracted at the air-core interface before transmission to the core-cladding interface at the critical angle. Hence any rays which are incident of the waveguide core at an angle greater than \( \theta_a \) will be transmitted to the core cladding interface at an angle less than \( \theta_c \), and will be totally internally reflected. This situation is illustrated in Fig 2.4, where the incident ray \( B \) at an angle greater than \( \theta_a \) is refracted into the cladding an eventually lost by radiation. Thus, for rays to be transmitted by total internal reflection within the waveguide, they must be incident on the core within an acceptance cone defined by the conical half angle \( \theta_a \). Hence \( \theta_a \) is the maximum angle...
to the axis at which light may enter the waveguide in order to be propagated, and is often referred to as the acceptance angle for the waveguide.

![Figure 2.3](image)

**Figure 2.3** Transmission of Light in a Perfect Waveguide

### 2.2.3 Numerical Aperture

The ray theory can be used to obtain a relationship between the acceptance angle and the refractive indices of the three media involved, namely the core, the cladding, and air.

![Figure 2.4](image)

**Figure 2.4** Acceptance Angle $\theta_a$ when Launching Light into an Optical Fiber

Figure 2.4 shows a light ray incident on the waveguide core at an angle $\theta_1$ to the waveguide axis which is less than the acceptance angle for the waveguide $\theta_a$. The ray
enters the waveguide from a medium (air) of refractive index $n_0$, and the waveguide core has a refractive index $n_1$, which is slightly greater than the cladding refractive index $n_2$. Assuming the entrance face at the waveguide core to be normal to the axis, then considering the refraction at the air-core interface and using Snell's law:

$$n_0 \sin \theta_1 = n_1 \sin \theta_2$$  \hspace{1cm} (2.3)

$$\varphi = \frac{\pi}{2} - \theta_2$$  \hspace{1cm} (2.4)

where $\varphi$ is greater than the critical angle at the core-cladding interface.

Hence, Eq. 2.3 becomes

$$n_0 \sin \theta_1 = n_1 \cos \varphi$$  \hspace{1cm} (2.5)

Since $\sin 2 \varphi + \cos 2 \varphi = 1$ then

$$n_0 \sin \phi_1 = n_1 (1 - \sin 2 \varphi)^{1/2}$$  \hspace{1cm} (2.6)

When the limiting case for total internal reflection is considered, $\varphi$ becomes equal to the critical angle of the core-cladding interface and is given by Eq. (2.2). Also, in this limiting case $\theta_1$ becomes the acceptance angle of the waveguide $\theta_a$. Combining these limiting cases into Eq. (2.6) gives:

$$n_0 \sin \theta_a = (n_1^2 - n_2^2)^{1/2}$$  \hspace{1cm} (2.7)

The above equation, apart from relating the acceptance angle to the refractive indices, serves as the basis for the definition of the important waveguide parameter, the numerical aperture (NA).

Hence, NA is defined as:

$$NA = n_0 \sin \theta_a = (n_1^2 - n_2^2)^{1/2}$$  \hspace{1cm} (2.8)
2.3 Modes in Waveguides

Starting again with an inner medium guide layer (n₁) and incident on to one of the dielectric surfaces with one of the confining layers (n₂), assume n₁ > n₂. Maxwell’s equations require that the transverse components of E and H and the normal components of D and B are continuous across the boundary. From this, several things follow. First and most important are the laws of refraction and total internal reflection discussed earlier. These laws depend on whether the angle of incidence, \( \phi \) is less than or greater than the critical angle \( \phi_c \). Next is the fact that some reflection occurs even when \( \phi < \phi_c \). this is known as Fresnel’s reflection. Because of the boundary conditions, the reflection coefficient is different for the components of the fields (E and H), which are parallel to or perpendicular to the interface. Then, when total internal reflection occurs, it is found that there is a phase change at the interface between the incident and reflected waves that varies with the angle of incidence. In terms of the ray model, this means that the reflection appears to take place at the surface lying behind the actual interface, an effect known as Goos-Hanchen shift.
Figure 2.5  Slab Waveguide

Now consider the waveguide shown in Fig. 2.5 in which two such dielectric interfaces are spaced a distance 2d apart. Consider a wave propagating in the guide layer in the positive z-direction. In the ray model, it would progress by multiple reflections as shown in Fig. 2.6. Such a ray can be thought of as representing a plane TEM wave travelling at an angle $\theta$ to the waveguide axis. It is seen that, while the phase velocity in the direction of propagation is

$$v_p = \lambda_m f = \omega/\beta_1 = c n_1,$$

the apparent phase velocity with which the wavefronts intercept any line parallel to the axis is

$$v_{p_z} = (\lambda_m \sec \theta)f = (\omega/\beta_1) \sec \theta = \omega/\beta \tag{2.10}$$

$$\therefore \beta = \beta_1 \cos \theta$$
In these equations, $\beta$ is the propagation constant of the plane TEM waves in the material of the guide layer.

![Diagram](image)

**Figure 2.6** Propagation by Multiple Reflection in Planar Waveguide

As discussed earlier, the limiting angle of obliqueness, $\theta_m$, is set by the critical angle, $\phi_c$, and is given by

$$\sin \phi_c - \cos \theta_m = n_1/n_2$$

(2.11)

Thus $\theta_m$ determines a minimum value for $\beta$ given by

$$\beta_{\min} = \beta_1 \cos \theta_m = \beta_1 n_2/n_1 = \beta_2$$

(2.12)

This means that rays parallel to the axis have a propagation constant near to $\beta_1$, whereas the most oblique guided waves have propagation constant, $\beta_2$, which is that of plane TEM waves in the confining layers. We expect $\beta_2 < \beta < \beta_1$. Fig 2.6 discusses another important property of the wave solution in terms of the ray model. This is the fact that only a finite number of discrete modes may propagate. In a diagram, these are represented as plane TEM waves and it is clear that if they are not to interfere
destructively after multiple reflections, then the distance $2d \csc \theta (1 - \cos \theta) = 4d \sin \theta$ must be an integral number of wavelengths.

Thus

$$\sin \theta_i = \frac{i\lambda_m}{4d} = \frac{i\lambda}{4n_1 d}$$  \hspace{1cm} (2.13)

where $i$ is an integer. Thus, only a finite number of discrete propagating angles satisfying Eq. (2.13) are permitted. Each of these corresponds to a particular waveguide mode with its own characteristic field distribution and its own propagation constant $\beta_i$, that we expect to lie between $\beta_1$ and $\beta_2$. Since $\theta_i \leq \theta_m$, the number of these modes is limited to

$$M = (4 n_1 d/\lambda) \sin \theta_m = (4d/\lambda)(n_1^2 - n_2^2)^{1/2}$$  \hspace{1cm} (2.14)

Note here that the $i^{th}$ guided mode can propagate only if $i\lambda \leq 4d (n_1^2 - n_2^2)^{1/2}$. At wavelengths longer than this, it is cutoff. The $i^{th}$ mode does not meet this condition for total internal reflection and is refracted at the dielectric interface. It does still satisfy the conditions for it to propagate freely in the confining layers and is said to be a radiation mode.

Expressions for the field distributions of the guided modes. There are two sets of guided wave modes having the form $\Psi = \Psi(x, y) \exp \{-j(\omega t - \beta z)\}$. These are the TE modes, in which $E_z$ is zero, and the TM modes, in which $H_z$ is zero. Discussion is restricted to the TE modes, which satisfy the equation

$$\frac{d^2 E_y}{dx^2} + \left[\frac{\omega^2 n_1^2}{c^2} - \beta^2\right] E_y = 0$$  \hspace{1cm} (2.15)
With \( n^2(x) = n_1^2 \) for \(-d < x < d\), and \( n^2(x) = n_2^2 \) for \( x < -d\) and \( x > d\). Furthermore, \( E_y \) and \( H_z \) (and hence \( \partial E_y / \partial x \)) are continuous at \( x = \pm d \). Thus, in the guide layer,

\[
\frac{d^2 E_y}{dx^2} + \left[ \frac{\omega^2 n_1^2}{c^2} - \beta^2 \right] E_y = \frac{d^2 E_y}{dx^2} + u^2 E_y = 0
\]

(2.16)

And in the confining layer

\[
\frac{d^2 E_y}{dx^2} - \left[ \beta^2 - \frac{\omega^2 n_2^2}{c^2} \right] E_y = \frac{d^2 E_y}{dx^2} + \omega^2 E_y = 0
\]

(2.17)

Putting

\[
u^2 = \omega^2 n_1^2 / c^2 - \beta^2 = \beta_1^2 - \beta^2
\]

(2.18)

and

\[
w^2 = \beta^2 - \omega^2 n_2^2 / c^2 = \beta^2 - \beta_2^2
\]

(2.19)

For the wave to be guided, it is necessary that \( u \) and \( v \) are both real. That is,

\[
\beta_1^2 = \omega^2 n_1^2 / c^2 > \beta^2 > \omega^2 n_2^2 / c^2 = \beta_2^2
\]

(2.20)

These conditions mean that the solutions in the guide layer are oscillatory, while those in the confining layers decay exponentially to zero at infinity.

For there to be a guided wave solution, then, the propagation constant, \( \beta \), has to lie between \( \beta_1 \) and \( \beta_2 \), as suggested by the ray model. This means that the phase velocities of the guided modes lie between \( w/\beta_1 = c/n_1 \) and \( w/\beta_2 = c/n_2 \). In particular, they cannot exceed the phase velocity of the plane TEM waves in the confining layers.

The electric field distributions for the guided modes take the form

\[
E_y(x) = E_s \cos ux
\]

\(|x| < d\)

(2.21)
OR

\[ E_y(x) = E_a \sin ux \]

and

\[ E_y(x) = E_c \exp(-|wx|) \quad (2.22) \]

where \( E_a, \ E_a, \) and \( E_c \) are constant values of electric field strength. The number of half periods of \( E_y \) that occur in the guide layer characterizes a given mode and determines the value of \( u \) and hence the propagation characteristics of that mode.

Application of the boundary conditions at \( \pm d \) enables the number of guided modes and their propagation parameters to be obtained. Consider a mode having \( m \) half-periods and therefore \((m-1)\) zero crossings. Let its propagation be characterized by \( u = u_m, \ w = w_m \). The boundary conditions require us to equate \( E_y(d) \) as given by Eq. (2.21) and (2.22). And likewise to equate the two expressions for \( dE_y(d)/dx \).

Thus for the symmetric modes

\[ E_y(d) = E_s \cos u_m d = E_c \exp(-w_m d) \quad (2.23) \]

and

\[ dE_y(d)/dx = -u_m E_s \sin u_m d = -w_m E_c \exp(-w_m d) \quad (2.24) \]

Dividing Eq. (2.24) by Eq. (2.25) gives

\[ w_m d = u_m d \tan u_m d \quad (2.25) \]

The corresponding expression for the antisymmetric modes is

\[-w_m d = u_m d \cot u_m d \quad (2.26)\]
These transcendental equations (2.25) and (2.26) may be solved graphically to provide values for \( u_m, w_m \) and hence \( \beta_m \), for any given value of the parameter \( V \), which is defined as:

\[
V = (u_1 + w_2)^{1/2} d = (\omega d/c)(n_1^2 - n_2^2)^{1/2} = (2\pi d/\lambda)(n_1^2 - n_2^2)^{1/2}
\] (2.27)

Thus the maximum number of modes a waveguide can support is equal to the next integer greater than \( 2V/\pi \). In this project, we have worked with single mode waveguides.

### 2.4 Summary

In summary, the size and the index of refraction difference \( n_1 - n_2 \) determines the number of optical modes propagating in the waveguides. This is important, since we would like to operate in the spectral region where only one mode is propagating through the waveguide (single-mode waveguide). The same applies to the ring waveguide. The theory for the ring waveguide is much more complicated and out of the scope of this thesis.
CHAPTER 3
FABRICATION OF WAVEGUIDES

3.1 Introduction

Any work in semiconductors requires a clean room environment with highly accurate and precise equipment. Any process during the fabrication process needs to be decided in advance before it is implemented. Before beginning the actual fabrication process, a traveler for the project is created. The traveler lists in detail the different processes to be carried out for the proper execution of the project. The traveler not only acts as a guide while working on a project but is also used to record certain observations while making the project.

3.2 Process of Fabrication

The following project was done in a state of the art Class 10 cleanroom at the Microelectronics Research Center at NJIT. The fabrication of the waveguides was done using CMOS grade silicon wafers. The detailed process of fabrication is explained below.

1) The first step is to clean the wafers thoroughly using M-pyrol. M-pyrol has two baths, one primary and one secondary. The secondary solution is fresher than the primary solution. Therefore, the wafers need to be dipped first in M-pyrol solution primary, and then in the secondary, each for 10 minutes. The temperature of both the primary and secondary should be set at 95° C for best results. Then the wafers were put in distilled water for 10 minutes. The resistance of the water is checked.
The resistance is more than 5 Ω's for a clean wafer. Then the wafers are spin dried in a drier. M-pyrol removes any organic dirt present on the wafers and makes it ready for P-clean.

2) After this process, the wafers are loaded into the P-clean carrier. The P-clean solution is a mixture of HF and H_2SO_3. Every morning the P-clean bath has to be dispensed with H_2SO_3 to make it effective. After dispensing, the wafers are put in the P-clean bath for 10 minutes. The bath should be at 110°C. After this, the wafers are dipped in hot water (80°C) for 10 minutes and then in cold water for another 5 minutes. This is necessary to bring down the wafer temperature slowly, to prevent any harm to the wafers. P-clean removes any superfluous oxide from top of the wafer surface.

![Figure 3.1](image)

Figure 3.1  CMOS Grade Silicon Wafer before Bonding

3) After the wafer cleaning process, the wafers need to be prepared for wet oxide deposition. The process of oxidation involves the following steps:
1) Furnace pre-clean
2) HF clean
3) Depositing oxide in the wet furnace

The first two processes need to be carried out just before putting the wafers in the furnace. If the process of P-clean was carried out on the wafers on the same day, it need not be repeated. Otherwise, it has to repeated again. The process is already described in Part 1. The cleaned wafers are put in the furnace pre-clean bath for 5 minutes. Then the wafers are put in distilled water for 10 minutes. The wafers are then spin-dried. These wafers are then inserted in 100:1 HF solution for 1 minute. They are then put in water and then dried. HF solution deposits a small amount of oxide on the wafers, which helps in proper oxide deposition. The cleaned wafers are then put in a closed clean container to prevent them from being exposed to the open air, which may contain dust particles. The wet oxidation furnace is then programmed for oxide deposition. The temperature is 1100°C and time required is about 11 hours. After removing the wafers from the furnace, the thickness of the oxide is measured. The deposited oxide on both the wafers should be about least 2 µm. The process of wet oxidation has an oxide growth rate of about 0.2 µm/hour. Though it is comparatively slow, the oxide deposited is fairly uniform and of good quality, which is helpful for wafer bonding.
4) The wafers with oxide are then bonded in a bonding machine. The force applied is 200 N for about 30 seconds. The bonded wafers are then inspected using an infrared camera. They are examined for any defects like air bubbles. Fig. 3.3 shows a bonded wafer with defects. The air bubbles trapped in between the two wafers can be clearly seen. While etching this wafer in KOH bath, some liquid can very easily creep in and break the bond.

Fig. 3.5 shows a perfectly bonded wafer. There are no striations or some other defects seen.
Figure 3.3  Bonded Silicon Wafers

Figure 3.4  Improperly Bonded Wafer. Air bubble trapped in between two wafers can be clearly seen.
Figure 3.5  Perfectly Bonded Wafer.
5) The bonded wafers after inspection and confirmation that the bond is strong, are taken for Annealing. Annealing strengthens the bond further. It also makes the bonding uniform. Annealing is generally done out at 1100°C and carried out for about 3 hours.

6) The annealed wafers are then allowed to cool and then are prepared to deposit nitride. The pre-cleaning procedures carried for depositing oxide are also carried out for Nitride deposition. The only difference is that the bonded wafers cannot be spin-dried as this may break the bond. So everytime the wafers are dried with a Nitrogen spray. The wafers are put in the Low Temperature Nitride deposition furnace. The time is about 2 hours for 20000 A. After removing the wafers from the furnace, they are inspected and thickness of nitride is measured.

7) The bonded wafer is then taken to the photolithography room. A thick layer of photoresist is applied on both sides of the wafer. Then one side of the wafer is exposed under a mask, with a hole in the center. A black paper with a hole in the center can also be used as a mask. The exposed side of the wafer is then developed using a developer and dried. Then the wafers are etched using Phantom plasma etch. While etching, a ring with a hole in the center is placed on top of the wafer to protect the edges. The time required for etching is about 120 seconds. The wafer is visually inspected at regular intervals and checked to see if all the
nitride and oxide is etched out. Since the oxide etch can etch both oxide and nitride, the file loaded in the Phantom etch is oxide.

![Diagram of wafer with nitride and coated with photoresist](image)

**Figure 3.6** Wafer with Nitride and Coated with Photoresist

8) The wafer is then taken to the photolithography room and cleaned with acetone to remove the coated photoresist. The wafer is again visually inspected. The nitride on those parts of the wafer, which are no going to be etched, should be intact. If the Phantom etch has affected the nitride on other parts, nitride needs to be deposited again and the process repeated. Even a small exposed area can be harmful, as KOH, which is used for etching silicon, can creep through the exposed part, and damage the wafer.
9) The wafer is now ready for etching. The wafer is immersed in a KOH bath. Bubbles should be seen emanating from the exposed surface. The etch rate is about 1.2 um/sec when the KOH is fresh. It decreases, as the KOH becomes old and saturated. The etch rate also decreases as we go deep inside the silicon wafer. Periodically the wafer is removed from the KOH bath, cleaned in water and inspected. The depth of silicon etched is also measured. Initially when the depth is less, DEKTAK can be used. However, as the depth increases it is measured with a microscope. The wafer has to be etched until the thickness of silicon reaches about 2 microns. At this point, the color of the surface looks orangish, and the underlying oxide can be seen. The silicon becomes transparent. This is the point when the etching should be stopped. In addition, when the thickness of the wafer becomes about 50 microns, the temperature of the bath is reduced to 70 degrees. By doing this, the etch rate of silicon reduces but a smoother finish is obtained. The smoother finish is required to do
photolithography on the wafer and a smoother finish helps in achieving a good pattern on the wafer. Fig. 3.8 shows a schematic of a wafer being etched in a KOH bath.

![Figure 3.8 Wafer being etched in KOH Bath](image)

10) After the thickness of the silicon left is about 2 microns, the wafer is taken out of the KOH bath. Before taking the wafer to the photolithography room it is required that the wafer be cleaned thoroughly as the KOH bath is considered highly corrosive. Hence, the wafer is cleaned using the RCA strip bath.

11) After the RCA strip procedure is finished, the wafer is taken to the photolithography room. The appropriate mask is loaded on the Exposure machine. The development time is set to about 16 sec. Photoresist is applied on the wafer surface. The speed for the spinner is kept at 2500 rpm, slightly higher than the normal speed. This is done to decrease the thickness of the photoresist, as the pattern on the mask is small. The wafer is then kept on a hot plate for 1 minute.
and then on the cooling plate for 1 minute. The wafer is then exposed with the Hard Contact option on the exposure machine set. The exposed wafer is then kept on the spinner. Some developer is sprayed on the wafer. After a half-minute wait, some more developer is applied. After one minute, spinning the wafer applying and spraying some water remove the developer. The pattern on the wafer is then observed under a microscope. If the pattern is proper, the depth of the photoresist is measured with DEKTAK. Fig. 3.10 shows one such profile. The profile of the pattern given by the DEKTAK gives an idea of the shape of the pattern. When the wafer is etched using Phantom plasma etch to get the pattern, some photoresist is also consumed. The depth of the pattern on the wafer should be at least 2 microns. So the depth of the photoresist should be at least 0.7 microns. Fig. 3.11 shows a profile after etching. It can clearly be seen from the profile, that the wafer has been etched.

**Figure 3.9** Wafer being exposed to UV Rays
12) After it is confirmed that the pattern is true to the specification, the wafer is put in
the Phantom plasma etch. The process file is set to Silica. The wafer etch time is
set to 120 sec. The profile of the pattern on the wafer is regularly inspected with
DEKTAK. After the depth of the pattern is as required, the photoresist on the
wafer is removed using M-pyrol. The M-pyrol process is described in Step 1. The
wafer is then inspected with DEKTAK.
Figure 3.10  Wafer with Photoresist before M-pyrol

Figure 3.11  Wafer after Removal of Photoresist by M-pyrol
Figure 3.12  

(a) The surface profile of the wafer measured with a DEKTAK before etching. The height of the pattern seen is equal to the height of the photoresist.

(b) Similarly measured profile after etching. The height of the pattern is equal to the height of the photoresist and the depth of the silicon etched.
13) The wafer now needs to be deposited with oxide. The wafer is cleaned and all pre-cleaning processes described in Step 2 are repeated. The wafer is then placed in the PECVD. The time required is about 15 minutes for an oxide thickness of about 500 Angstroms. The thickness of the oxide is then measured.

![Diagram of wafer with layers]

**Figure 3.13** Final Wafer with Oxide

14) The above procedure is repeated for another pair of wafers. In this case the second mask is used. The first mask has a pattern for rectangular waveguides. The second mask has a pattern for ring waveguides.
Figure 3.14  Photo of the Waveguide taken through a Microscope
15) Figures 3.15 and 3.16 show the photographs of the rectangular waveguide as taken through a microscope. Figure 3.18 shows the photograph of the ring waveguide.

After the rectangular waveguides were fabricated, it was important to know the height of the waveguides. This data was obtained by optical profilometry in the Microelectronics research Center. The optical profilometer scans the surface of the wafer and generates a profile depending on the different heights. Following is some of the data obtained from the profilometer.
Figure 3.16   Photograph of the ring waveguide taken through an optical microscope.
Figure 3.17  Image of the Wafer Surface as obtained from Optical Profilometer.

Figure 3.18  X profile of the wafer surface as obtained from the Optical Profilometer.
As is evident from the above figures viz the surface scan and the X profile the average height of the waveguides is about 1.5 microns.

16) Each wafer is now cut using a proper cutting procedure into a group of waveguides. The wafers are now ready to be bonded together. Before they can be bonded together the rectangular and the ring waveguides need to be aligned with each other. This alignment procedure had to be done very carefully, as the pieces of the wafer were small and very delicate. Hence, the pieces were first stuck on a microscope cover glass so that handling of the wafers was facilitated. Now the cover glass with the ring waveguides was placed inverted over the cover glass with the rectangular waveguides and this combination was placed under an IR microscope. Both the waveguides were aligned with the help of the IR microscope and then glued together.
Figure 3.19  Crosssection of the final wafer with the rectangular waveguides.

Figure 3.20  Crosssection of the final wafer with the ringwaveguides.
Figure 3.21 Cross section of the two wafers after gluing together.
Figure 3.22  Topview of the two glued wafers as taken through the IR microscope.
Figure 3.23  Image shows two such structures.
CHAPTER 4
EXPERIMENTS ON THE WAVEGUIDES

4.1 INTRODUCTION
Some experiments were carried out to measure the transmission through the rectangular waveguide. The chapter starts with an explanation of blackbody radiation and then explains how these experiments were conducted.

4.2 BLACKBODY RADIATION
Any body temperature above the absolute zero temperature emits spectral radiation. This radiation characteristic is subject to known laws and is normally represented as a function of blackbody radiation. A blackbody radiator is an idealized source of radiant energy, which also absorbs all radiation incident upon it. This is a perfect diffused radiator with a well-defined radiation spectrum. Since it is possible to build a close approximation of radiation properties of any surface to a blackbody, this concept is very useful in the calibration and testing of radiometric instruments. The parameter, which relates the radiation characteristics of any real body to that of a blackbody, is known as emissivity. Emissivity is defined as the ratio of the radiation emitted by the surface to the radiation emitted by the blackbody at the same temperature and for the same spectral and directional conditions. For a blackbody, emissivity is unity under all spectral and directional conditions.
Planck’s law relates the spectral radiant emittance (radiance) of a perfect blackbody to its temperature and the wavelength of the emitted radiation. The mathematical expression that describes the Planck’s radiation law is given as:

\[ L(\lambda, T) = \frac{2hc^2}{\lambda^5} \left( e^{\frac{hc}{\lambda kT}} - 1 \right) \quad [\text{W cm}^{-2} \text{ sr}^{-1} \text{ nm}^{-1}] \quad (4.1) \]

Where 
- \( h \) – is Planck’s constant, \( 6.6262 \times 10^{-34} \)
- \( \lambda \) – is wavelength in micrometers
- \( c \) – is the velocity of light, \( 2.997 \times 10^8 \) m/s
- \( k \) – is Boltzmann’s constant, \( 1.3806 \times 10^{-23} \) J/K; and
- \( T \) – is the absolute temperature in Kelvin (K).

Figure 4.1 illustrates the spectral distribution of blackbody radiation as a function of wavelength for a selected temperature range. The Planck’s radiation formula (4.1) shows that the spectrum of radiation shifts towards shorter wavelengths or longer wave numbers as the temperature of the radiator is increased.
4.3 Experimental Results

1) The first experiment was conducted to determine if transmission of light was possible through the waveguide. The experiment was conducted in the following manner. First the wafer was cut and the waveguide was exposed. A black body radiator was used to generate radiation with wavelength of the order of 5 microns. This radiation was then passed through a lens and focused on the waveguide core. The light, which passed through the waveguide, was also passed through a lens and imaged onto a CCD camera. The output from the CCD camera was obtained on the terminal. Following figures depict the setup for the experiment and some of the images that were obtained from the camera.
Figure 4.2  Experimental setup for transmission of light through a waveguide

Figure 4.3  CCD Image of the waveguides.
Figures 4.3 and 4.4 depict the images of the waveguide as obtained through the CCD camera. In figure 4.3 the white spots indicate the presence of waveguides. The spots that are seen is the light passing through the waveguides. In figure 4.4 the single white spot obtained is the light passing through a single waveguide.
Figure 4.5 Photograph of the experimental setup. Shows the Blackbody radiator the lenses and the waveguide placed in between the lenses.
Figure 4.6 Photograph of the full setup. Shows the Blackbody radiator, lenses, the Microscope and the CCD camera.
2) The second experiment was conducted after the two wafers were glued together. The experimental setup used was the same as for the previous experiment. Following are some of the images obtained from the CCD camera.

*Figure 4.7* Image of light passing through the glued combination of the two waveguides.

In the above figure the white spots indicate the area where the waveguide is located.
VLSI technology may have a great impact on the manufacturing and processing of optical devices.

It has been shown that an optical filter can be manufactured using wafer bonding and standard wafer processing techniques. On the other hand such procedures pose some challenges, which are important to overcome.

The first challenge is in the use of KOH as an etchant for silicon. KOH is highly corrosive and hence leaves surface of the wafer very rough after etching. Although care was taken to reduce the temperature of the KOH bath as etching was nearing its finish, still the surface obtained was rough. The rough surface of the wafer makes photolithography difficult and a lot of time was spent and numerous recipes were tried before a reasonably good pattern was obtained on the wafer. Hence, an alternative to KOH is required which will serve a dual purpose of etching silicon and at the same time leaving the wafer surface smooth and suitable for photolithography. A second challenge was encountered after the pattern was obtained on both the wafers. Oxide was to be deposited on the wafers. If the conventional way of depositing oxide were to be used, then the deposition technique would eventually grow oxide by etching the top layer of the silicon. This would eventually reduce the pattern on the wafer. Hence, another technique of oxide deposition was used (PECVD) which deposits oxide on the wafer surface rather than growing it as in the conventional method. This oxide layer cannot be used for
bonding. Instead glue was used to bond the wafers. Another challenge was that the pieces to be bonded were very small in size and could not be bonded in a standard bonding machine.

5.2 Conclusion
Wafer bonding can be a very efficient method of manufacturing integrated optical multiplexer/demultiplexers. It can also be concluded that silicon is a very suitable material for making such structures. The use of VLSI technologies in fabricating optical elements may therefore advance the area of optical networking and sensing.

5.3 Future Developments
A number of additions can be made to the basic resonator structure. Some of these improvements are discussed below.

5.4 Multiple Ring Structure for Better Spectral Filtering
In this project, a ring waveguide was used as a resonant filter. In such a geometry, the forward propagating wave in the bus excites a rotating mode in the ring, which in turn couples into the backward propagating mode in the drop. Ideally, at resonance, 100% transfer can be achieved. However, radiation losses and bending losses inside the ring have the effect of reducing the transfer efficiency. Furthermore, the ring waveguides supports multiple resonances.
Figure 5.1  Multiple Ring Structure for Better Spectral Filtering

A multiple-ring design can also be used to increase the free spectral range, which measures the mode spacing between the frequency channels. Each ring has a different radius, and supports a different set of resonant frequencies. Maximum transfer occurs only when the resonant frequencies of both rings match with each other. Although the multiple ring geometry can increase the free spectral range of the CDF, the transfer efficiency suffers severe reduction.

In addition to the multimode nature of a ring cavity, the quality factor is limited by intrinsic radiation losses and degrades significantly with even a moderate amount of surface roughness. It is therefore of great practical interest to explore the possibilities of using photonic crystal microcavities in a channel drop filter.
REFERENCES


