Strip-loaded slot waveguide for highly integrated photonics

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Abstract

The purpose of this master thesis was to demonstrate the effect of a patterning on the strip-loaded slot waveguide platform. The focus was mainly on the Bragg grating structures and to evaluate the influence of the geometrical variations on the SLSW platform which has a low index contrast. The different Bragg grating structures were designed using the FDTD software. The objective was to observe the fluctuation in the photonic band gap by the periodic variation of the effective index along the propagation direction of the SLSW platform. The SLSW structure was fabricated using atomic layer deposition and spin coating. The waveguide was then exposed to electron beam lithography for patterning the nano-structures. The fabrication lead to the fluctuation of various structure parameters. As a result, the structures were re-simulated using the fabricated parameters and characterized to show the response of the SLSW platform.
Preface

I am extremely delighted to present my master thesis on “Strip-loaded slot waveguide for highly integrated photonics”. The work was completed under the supervision of Assistant Professor Matthieu Roussey at University of Eastern Finland, Joensuu.

First of all I would like to express my gratitude to my supervisor Matthieu Roussey for his constant guidance and instructions during the span of thesis work. I am thankful to the early stage researchers Arijit Bera and Somnath Paul for sharing their valuable knowledge during the course of the work. I would also like to thank deeply MSc Ségolène Pélisset for her time, patience and effort in mentoring me in the clean room and the experiments. I would like to extend my regards to our course coordinator Noora Heikkilä for providing the necessary information, assistance and guidance throughout the entire span of the master degree. I am thankful to the Department of Physics and Mathematics and the University of Eastern Finland for providing me with all the required facilities for these two years.

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Integrated silicon photonic is born with the first realization of waveguides on silicon-on-insulator (SOI) wafers in 1985 by Soref and Petermann [1] and their first commercialization was started in 1989 by Bookham Technology Ltd [2]. Since then, the development of silicon photonics has grown rapidly [3–6]. In recent years, silicon has been developed as an effective practical platform for integrated photonics [7,8]. It has been accepted universally as a leading technology in the future communication system as it leads to the advantage of integration and photonics, i.e., transmission of a high-density data over a long distance involving platforms, where a high level of integration can be achieved with a low manufacturing cost [9]. Thus silicon can prove its excellence in complex integrated photonic systems.

Initially, the development of silicon photonic structures started with large ridge waveguides having a cross section of several micrometers. Now structures have been reduced to sub-micron scale. The high index contrast provided by silicon (Si) and silicon dioxide (SiO\textsubscript{2}) in silicon structures enables researchers to design highly confining waveguides. This not only leads to a high intensity of light within the waveguide but also generates nonlinear effects, like Raman (1000 times stronger than in silica fiber) and Kerr (100 times stronger than in silica fiber) effects within the structure [10]. This, in turn, facilitates certain optical functions like amplification, lasing and wavelength conversion which was beyond the scope of silicon. The current research works are addressed to the integration of a number of components on a common waveguide platform that is required for telecommunication applications. [11,12]

In recent years, scientists have overcome the challenge of integrating the basic
building blocks of the circuits on the SOI wafer. The building blocks comprise of the active components, e.g., modulators and photodetectors, and the passive components, e.g., waveguide, filters, distributed Bragg reflectors and grating couplers. Due to the high integrability and the low cost manufacturing of silicon photonics, a vast change has been experienced in every aspect of our daily lives. Apart from data communication, silicon photonics is nowadays being used in the commercial and academic world. These include, for instance, nonlinear optics [13], biosensing [14], gas sensors [15], optical gyroscopes [16], light detection and ranging systems (LiDAR) [17], light sources [18], long wavelength integrated photonics [19].

One of the biggest concern of recent times is the power consumption of the devices. According to the demand of the modern industries, devices must more efficient, small, cheap and operating under low power. To be more efficient, optical components have to present an increased light-matter interaction, usually obtained by using micro and nano-structures, which yields to a smaller feature size and enhances the effect in the devices. Amidst all the advantages, one of the prevailing challenges of silicon photonic integrated structures is losses. The propagation losses due to scattering from rough sidewalls and coupling losses are dominant among them. To overcome this problem, a novel structure has been proposed, which shows a high confinement of light, better integrability and can be easily fabricated at a low cost. The structure consists of a horizontal slot waveguide with a loading strip on the top. Light is guided and confined vertically through the horizontal slot which is further confined in the lateral direction by the loading strip [20].

The aim of this thesis is to design and characterize Bragg gratings on this new waveguide platform. Bragg gratings have always been of much importance because of their large field of applications. They can be utilized as optical filters to compensate the chromatic dispersion and also as optical add/drop multiplexers in dense wavelength division multiplexing (DWDM) in optical fiber communication [21]. It is also widely used as optical sensors because its reflected wavelength is sensitive to temperature and strain [22]. The gratings are constructed in such a way that it appears to be perpendicular to the direction of the propagation of light. The diversity of the structure can be increased by modulating the period of the gratings, the number of periods and the fill factor, and by changing the shape of the features. The purpose of this work is to simulate and characterize Bragg gratings by varying the various parameters and observing the corresponding effects.
In this chapter, we will briefly describe the theoretical background needed for the understanding of the work done during my master thesis. It includes the theory of optical waveguides and their different geometry, generalities about photonic crystal and in particular Bragg gratings, and finally the effective index approximation.

2.1 Optical waveguides

A spatially inhomogeneous structure that can guide electromagnetic waves is known as an optical waveguide. Light propagates through the structure following the laws of total internal reflection. A waveguide is a particular arrangement of materials with different refractive index, allowing the confinement of light in a particular region, the core, while the surrounding medium is called cladding. Usually, the refractive index of the material composing the core is higher than the one of the cladding. Depending on the geometry, optical waveguides can be classified into the slab waveguides, channel waveguides, and optical fibers, which can also be considered as channel waveguide with cylindrical geometry.

2.1.1 Slab waveguide

A dielectric slab waveguide has a simple planar geometry (see Figure 2.1). Hence, it is also known as the planar waveguide. Such a waveguide is assumed to have a core region with a refractive index \( n_1 \) deposited on a substrate with refractive index \( n_2 \). The region above the core may be air or any other dielectric medium having a refractive index \( n_3 \), such that, \( n_1 > n_2 \geq n_3 \). The waveguide extends infinitely in the \( x \) and \( z \)-direction, i.e., the horizontal direction and the direction of the propagation
of light respectively. The propagating light is confined only in the vertical direction. Both, transverse electric (TE) and transverse magnetic (TM) modes exist in a slab waveguide. In TE modes, the electric field is present in the direction parallel to $x$-axis and the magnetic field is present in the $yz$-plane. While, in TM modes, the magnetic field is present in the direction parallel to $x$-axis and the electric field is present in the $yz$-plane.

Figure 2.1: Dielectric slab waveguide.

2.1.2 Channel waveguide

Unlike the slab waveguide, a channel waveguide does not have any invariance in the $x$-direction. This leads to a confinement of light in both the vertical and horizontal direction. A channel waveguide can support TE and TM modes along with some hybrid modes, i.e., where TE and TM modes are present simultaneously. Depending on the geometry of the core, the channel waveguides are further classified into the strip waveguide, slot waveguide, strip loaded waveguide, rib waveguide, buried waveguide and so on. Each of them exhibits different properties. The following sections present an overview of the most common types of waveguides used in integrated optics.

2.1.2.1 Strip waveguide

The ridge or strip waveguide, as shown in Figure 2.2(a), consists of a strip of high index material ($n_H$) on a substrate with a lower refractive index ($n_S$). As the
surrounding has a lower refractive index \((n_L)\) than the strip, light is confined and propagates through the high index medium. The main part of light is confined in the strip which provides both lateral and transverse confinement. These waveguides are extensively used in photonics due to their versatility in terms of application, the large choice of materials they can be made of, and their relatively easy fabrication. The propagating light suffers scattering losses due to the roughness of the vertical edges of the strip. The propagation losses for silicon nitride strip waveguide is recorded to be around 4 dB/cm at 1550 \(\mu m\) [23]. Silicon strip waveguide with losses as low as 3.6 dB/cm has been demonstrated [24]. Recently, propagation loss for amorphous titanium dioxide strip waveguide was reduced from 5.0 \(\pm\) 0.5 dB/cm to 2.4 \(\pm\) 0.2 dB/cm at 1.55 \(\mu m\) by reducing the sidewall roughness, which is one of the main source of loss, by using atomic layer re-deposition of the same material than the waveguide core [25].

![Figure 2.2](image)

**Figure 2.2**: Schematic diagram of the cross-section and the mode confinement of (a) Strip waveguide, (b) Slot waveguide and (c) Strip loaded waveguide.

### 2.1.2.2 Slot Waveguide

A slot waveguide consists of two rails of high refractive index material \((n_H)\), separated by a thin gap of low refractive index medium \((n_L)\), ideally air, shown in Figure 2.2(b). The high index contrast between the materials causes a discontinuity in the electric field. The electric field discontinuity at the high index contrast interfaces (at the walls of the rails) causes the evanescent tails of the propagating modes to interact constructively when the two rails are close enough (few tens of nanometers). This leads to a high confinement of light in the low index region, which is not usual.
In 2004, Almeida et al. introduced the concept of slot waveguide [26] and performed the experimental demonstration [27]. They experimentally presented the confinement of the quasi-TE mode (the electric field component $E_x$ is perpendicular to the walls of the slot) in the air slot. This property of the structure is advantageous in the field of sensing, nonlinear optics, telecommunication etc [28–31]. However, any surface roughness introduced during fabrication leads to high scattering losses. To minimize the scattering losses, horizontal slot waveguide structure was designed. Here, the low index slot region is sandwiched between two horizontal high index rails. In this case, the confined power within the slot depends on the thickness of the rails, while the effect on the slot thickness is minimal. Paul Müllner and Rainer Hainberger concluded from their study [32], that a maximum confinement of the optical power in the slot with minimum scattering losses can be obtained from the structure (Si/SiO$_2$ slot waveguide) proposed by Barrios et al. [33, 34].

### 2.1.2.3 Strip loaded waveguide

The strip loaded waveguide as shown in Figure 2.2(c) consists of a strip of low refractive index material ($n_M$) patterned on top of a planar waveguide of higher refractive index material ($n_H$). The slab waveguide confines the propagating light in the vertical or the $x$-direction. The loading strip causes a variation in the effective index which confines light in the horizontal or the $y$-direction. This structure was first introduced by Furuta et al. [35]. The roughness of the vertical edges of the loading strip are no more a matter of much concern as the maximum energy of the propagating light is confined in the planar waveguide. V. Ramaswamy experimentally demonstrated the number of modes that can be supported by the waveguide [36]. Another study on the strip loaded diffused waveguide illustrated, to obtain a single mode guide for a structure having a strip of titanium (Ti), the width of the strip should be narrower than 7 $\mu$m [37]. A contemporary work by Uchida stated that a high index loading strip allows a larger confinement of the optical energy compared to the low index loading strip [38].

### 2.2 Strip loaded slot waveguide

In this work we have used a novel waveguide structure, a strip loaded slot waveguide (SLSW) [20, 39]. It has been demonstrated experimentally that the structure
provides a high confinement of light and also allows integration of micro-structures. The SLSW comprises of a horizontal slot waveguide with a polymer strip on the top of the upper rail of the slot. The horizontal slot provides a vertical confinement of light. The strip on the top of the slot waveguide induces a variation in the effective index. This provides the confinement of light in the horizontal direction. Thus the maximum energy of the propagating light is confined in the region of the slot lying under the strip. However, the amount of light interacting with the upper or the lower rail can be controlled by adjusting the thickness of the rails. The micro-structures are patterned on the strip. Layers composing the slot waveguide can be extremely smooth (depending on the deposition technique), minimizing the roughness at the interfaces. Since light is confined far below the patterned surface (the loading strip), it experiences very low scattering. The structure allows the propagation of several quasi-TE modes along with the fundamental quasi-TM slot waveguide mode, which is of our concern in this work.

![Cross-section of a strip loaded slot waveguide.](image)

**Figure 2.3:** Cross-section of a strip loaded slot waveguide.

Figure 2.3 represents the cross-section of the SLSW that has been used for our work. The low refractive index medium of the slot consists of silicon dioxide ($\text{SiO}_2$) having a refractive index $n_{\text{SiO}_2} = 1.444$, sandwiched between two layers of high refractive index medium, titanium dioxide ($\text{TiO}_2$) with a refractive index $n_{\text{TiO}_2} = 2.27$ at $\lambda = 1550$ nm. The strip on the top of the slot waveguide is made of a polymer...
AZ® nLOF 2070, having a refractive index $n_{\text{strip}} = 1.601$. The thickness of the slot region is $t_s = 80$ nm, and the thickness of the upper and the bottom layers are $t_u = 200$ nm and $t_b = 180$ nm, respectively. The thickness of the polymer strip is set to $t_p = 250$ nm and the width is $w_p = 1.2$ $\mu$m. All these parameters are designed for $\lambda = 1550$ nm, in order to obtain a single mode (quasi-TM polarization) waveguide.

2.3 Wave equation of the SLSW structure

For the propagation of light through the SLSW we should consider the electromagnetic wave theory. According to Maxwell’s equation, we have,

$$\nabla \times \mathbf{E}(\mathbf{r}, t) = -\mu \frac{\partial \mathbf{B}(\mathbf{r}, t)}{\partial t}$$ (2.1)

$$\nabla \times \mathbf{H}(\mathbf{r}, t) = \varepsilon \frac{\partial \mathbf{D}(\mathbf{r}, t)}{\partial t}$$ (2.2)

$$\nabla \cdot \mathbf{D} = 0$$ (2.3)

$$\nabla \cdot \mathbf{B} = 0$$ (2.4)

where $\nabla$ is a vector operator, $\mathbf{E}$ is the electric field vector, $\mathbf{H}$ is the magnetic field vector, $\mathbf{D}$ is the electric flux density vector and $\mathbf{B}$ is the magnetic flux density vector. The electric and the magnetic flux densities can be further defined as,

$$\mathbf{D} = \varepsilon \mathbf{E}$$ (2.5)

$$\mathbf{B} = \mu \mathbf{H}$$ (2.6)

where, $\varepsilon = \varepsilon_0 \varepsilon_r$ is the dielectric permittivity of the medium and $\mu = \mu_0 \mu_r$ is the magnetic permeability of the medium. Now substituting equation (2.5) and (2.6) in the equations (2.1) to (2.4) we get the following.

$$\nabla \times \mathbf{E}(\mathbf{r}, t) = -\mu \frac{\partial \mathbf{H}(\mathbf{r}, t)}{\partial t}$$ (2.7)

$$\nabla \times \mathbf{H}(\mathbf{r}, t) = \varepsilon \frac{\partial \mathbf{E}(\mathbf{r}, t)}{\partial t}$$ (2.8)

$$\nabla \cdot \varepsilon \mathbf{E}(\mathbf{r}, t) = 0$$ (2.9)

$$\nabla \cdot \mu \mathbf{H}(\mathbf{r}, t) = 0$$ (2.10)
Now, we assume that the waveguide is infinitely extended in the \(xz\) plane. If we consider time harmonic fields, then the time dependence can be expressed as a complex notation, \(e^{i\omega t}\). Again, the \(z\) dependence of the mode fields within the waveguide can be expressed as a function, \(e^{-i\beta z}\). The fields can then be expressed as,

\[
\begin{align*}
\mathbf{E}(\mathbf{r}, t) &= \mathbf{E}(\mathbf{r}, t)e^{i(\omega t - \beta z)} \\
\mathbf{H}(\mathbf{r}, t) &= \mathbf{H}(\mathbf{r}, t)e^{i(\omega t - \beta z)}
\end{align*}
\] (2.11)

Now, since the SLSW supports only transverse magnetic mode of light, the modes have only \(E_z\), \(E_y\) and \(H_x\) components of the field. Therefore, Maxwell’s equations are reduced to,

\[
\begin{align*}
i\beta H_x &= -i\omega \varepsilon E_y \\
\frac{\partial H_x}{\partial y} &= -i\omega \varepsilon E_z \\
\frac{\partial E_z}{\partial y} + i\beta E_y &= -i\omega \mu_0 H_x
\end{align*}
\] (2.13-2.15)

The tangential component of the electric field \(E_z\) and that of magnetic field \(H_x\) are continuous. As a result \(\varepsilon^{-1}(\partial H_x/\partial y)\) is also continuous. Moreover, as the materials are considered to be non magnetic and \(\varepsilon_r = (1/n^2)\), \(n^{-2}(\partial H_x/\partial y)\) is also continuous. Hence, the wave equation is as follows,

\[
\frac{n^2}{\varepsilon_r} \frac{\partial}{\partial y} \left( \frac{1}{n^2} \frac{\partial H_x}{\partial y} \right) = (\beta^2 - n^2 k_0^2) H_x
\] (2.16)

By solving the above equation, we can determine the solutions for \(H_x(y)\) for the different layers of the structure [39].

### 2.4 Photonic crystal

Photonic crystals are periodic arrangements, in one, two, or three dimensions, at the sub-wavelength scale, alternating low and high refractive index media. Introduced in 1989 by Yablonovitch [40] and John [41], these structures have the particularity...
to present photonic forbidden bands in their transmission spectra. These Photonic Band Gaps (PBGs) are the spectral range of wavelengths for which no light can propagate through the structure.

Application of photonic crystals as a solution for the reduction of integrated components footprint have been extensively studied. From Lasers [42,43] to sensors [44,45], many research groups have focused their activities on this field. However, a photonic crystal scatters light and is the source of losses [46], which is to be avoided in integrated optics.

2.5 Bragg gratings

A one-dimensional photonic crystal patterned on a waveguide is called a Bragg grating. It can be created by periodic modulation of the effective index of the waveguide. This can be achieved by modulating the refractive index or the dimension of the core region of the waveguide which guides the light. The propagating light reflects with every modulation of the refractive index. The periodic modulation causes multiple reflections of the propagating light. The wavelength at which all the reflected light are in phase and add up constructively to form the backward reflecting light is called the Bragg wavelength (\( \lambda_B \)) defined by equation [47],

\[
\lambda_B = 2n_{\text{eff}}p
\]

where, \( n_{\text{eff}} \) is the effective index of the waveguide and \( p \) is the grating period [48]. In case of a low contrast (strip loaded) waveguide this approximation is sufficient to estimate, as a first hint for the further design, the central wavelength of the photonic band gap. The reflections of light at the other wavelengths cancels out each other and as a result, these wavelengths are transmitted through the grating. In 1978, Hill et. al. first demonstrated the development of periodic grating by modulating the refractive index of an optical fiber with UV exposure [49]. Bragg gratings are widely used in sensing applications [50,51].

2.6 Effective index approximation

The effective index approximation is a simplification technique involving the effective index of the waveguide in the calculation of the modal properties of a complex three-
dimensional structure. This approximation is made to reduce a 3D structure to an effective 2D refractive index profile. First, the effective index for the TM mode is calculated considering invariance in the $x$-direction (slab waveguide case) in the region without the strip and the region with the strip, as in Figure 2.4(a). Next, as shown in Figure 2.4(b), the vertical regions of the layers of materials are replaced by their respective effective indices.

![Figure 2.4: Effective index approximation of the strip loaded slot waveguide.](image)

(a) Effective index of the cross section of the 3D structure. (b) 3D structure reduced to 2D with the application of the approximation.

The effective index approximation is extremely useful for the simulation of complex structures. Errors may occur in the calculations of the losses as this method is an approximation [52]. It is a matter of concern that the approximation is valid for a structure with low index contrast. In the case of a high index contrast structure, the approximation is valid only for a narrow band of frequency. The structure we are interested in (SLSW) has a low effective index contrast between the different regions (regions with and without the strip). Therefore, the approximation made for the structure is valid. The $n_{\text{eff}1}$ and $n_{\text{eff}2}$ can be calculated using Fourier Modal Method (FMM) and measured (after fabrication) using a prism coupler.
This chapter deals with the design and simulation of our nano-photonic structures on the SLSW platform. Most of the simulations have been performed using the Finite Difference Time Domain (FDTD) method.

### 3.1 The Finite Difference Time Domain method

Finite difference time domain method (FDTD) is a numerical method used for solving the interaction of electromagnetic fields with physical objects and the environment [53]. The technique was first proposed by Kane S. Yee, so the method is also known as the Yee’s method [54].

The FDTD solves Maxwell’s equation in space and time. The two curl Maxwell’s equations, relating the electric and the magnetic field of a wave, are discretized in a spatial and a temporal mesh. Each component of the electromagnetic fields are calculated at each position in space and at each time step. That is, the present value of the \( \mathbf{E} \)-field in time, at any point in space, depends on the previous value of the \( \mathbf{E} \)-field and the numerical curl of the \( \mathbf{H} \)-field in space. Similarly, the \( \mathbf{H} \)-field is also time-stepped. At any point in space, the present value of the \( \mathbf{H} \)-field in time is dependent on the previous value of the \( \mathbf{H} \)-field and the numerical curl of the \( \mathbf{E} \)-field in space. The most common spatial mesh used is a rectangular Cartesian mesh defined by a unit cell: the Yee cell [54]. Since equations are solved within the time, the result of the calculation is the time dependence of the electromagnetic field, which can lead by simple Fourier transform operation to the spectral response of any complex optical geometries.

In order to understand the theory behind the FDTD method we consider a one
dimensional problem. We assume the propagation medium to be a free space. Thus Maxwell’s equations can be written as follows,

\[
\frac{\partial \mathbf{E}}{\partial t} = \frac{1}{\varepsilon_0} \nabla \times \mathbf{H} \tag{3.1}
\]

\[
\frac{\partial \mathbf{H}}{\partial t} = -\frac{1}{\mu_0} \nabla \times \mathbf{E} \tag{3.2}
\]

Since the structure is one dimensional and considering a propagation along the \(z\)-direction, only \(E_x\) and \(H_y\) components of the field exists. Thus the equation (3.1) and (3.2) are reduced to,

\[
\frac{\partial E_x}{\partial t} = -\frac{1}{\varepsilon_0} \frac{\partial H_y}{\partial z} \tag{3.3}
\]

\[
\frac{\partial H_y}{\partial t} = -\frac{1}{\mu_0} \frac{\partial E_x}{\partial z} \tag{3.4}
\]

Now by following Yee’s algorithm, the \(E_x\) and \(H_y\) fields are shifted both in time and space. This leads to the central difference approximation of the derivatives. Thus the equations (3.3) and (3.4) can be expressed as follows,

\[
\frac{E_x^{n+1/2}(k) - E_x^{n-1/2}(k)}{\Delta t} = -\frac{1}{\varepsilon_0} \frac{H_y^n(k + 1/2) - H_y^n(k - 1/2)}{\Delta z} \tag{3.5}
\]

\[
\frac{H_y^{n+1}(k + 1/2) - H_y^n(k + 1/2)}{\Delta t} = -\frac{1}{\mu_0} \frac{E_x^{n+1/2}(k + 1) - E_x^{n+1/2}(k)}{\Delta z} \tag{3.6}
\]

In these two equations, \(\Delta t\) is the time step, \(\Delta z\) is the spatial step, \(k\) is the integer related to the space discretization, and \(n\) the integer related to time. One can see from the equation 3.5 and 3.6 that the fields at time \(n\) are calculated as a function of the fields at time \(n - 1\). This is the basic principle of the finite difference method, which expresses the derivative of a function using Taylor’s theorem.

One originality of the method (the Yee algorithm [55]) is the half a spatial and time period shift between the \(E\) and \(H\) fields.

### 3.2 Simulation software

The OptiFDTD software is a powerful tool that can simulate integrated and diffractive optical devices. It can model the propagation, diffraction, reflection, scattering
and polarization of light. It can also simulate devices in sub-micron scale having fine structures. The software is capable of simulating 2D as well as 3D structures. Therefore, the simulation domain consists of 2D or 3D mesh depending on the structure where each cell represents a small volume with defined material properties. [56]

FDTD simulation using OptiFDTD is completed following four main steps, using four different parts of the OptiFDTD software:

- **OptiFDTD Designer**
  It is the primary program of OptiFDTD. Here initially the simulation domain is defined. The wafer dimension, i.e., the calculation window (2D or 3D), and their properties (the length and the width) are specified here. For 2 dimensional wafers, the length which corresponds to the $z$-direction of the grid and the width that corresponds to the $x$-direction of the grid are set. Then the structure is designed by adding the components and specifying their dimensions. The software provides a wide list of components that can be used for the design of our structure which includes the linear waveguide, S-bend waveguides (arc, sine and cosine), PGB crystals etc. Then the input plane, i.e., the light source, is defined which may be a continuous wave or a pulse wave. Its shape (Gaussian, rectangular etc.) can also be defined according to what is required for the design of the specific structure. Finally, the observation region is defined. The observation region can be a point, a line, or an area. The input parameters of the software should be entered in micrometers ($\mu m$). The data files are saved with an extension of ".ftd", easily opened with Matlab for very advanced data processing, or the conventional analyzer software which belongs to OptiFDTD.

- **Profile Designer**
  In this program, the profiles and the materials constituting the different components, used in OptiFDTD Designer, are defined. These parameters are mainly the dimensions as well as the refractive index. Note that for 2D structures, the effective index for the different profiles are specified.

- **OptiFDTD Simulator**
  This program is used to run the simulation. The simulation can be done either TE or TM mode. For 2D simulations the size of the mesh along the $x$-direction
and $z$-direction are assigned in $\mu m$ (For our design, the mesh size was set to 0.05 $\mu m$ and 0.025 $\mu m$ along the $x$ and $z$-direction respectively). The time steps and the time sampling intervals can also be specified. A tradeoff has to be obtained in between the size of the mesh and the time step to obtain an accurate result. The smaller the size of the time step and the mesh, the longer and better is the simulation results.

- **OptiFDTD Analyzer**

Once the simulation is complete, the file is loaded with the help of the analyzer to view the result. In this window, the layout, 3D view, as well as the refractive index distribution of the designed structure can be viewed. From the analyzer, we obtain the distribution of the amplitude, intensity, phase etc. of the transmitted spectrum at the observation regions that have been assigned in the design. When the observation region is a point, the analyzer can give, among other information, the time dependence of the field at that point. This allows, via a fast Fourier transform, the calculation of the spectrum. Observation lines and areas enables the investigation of the field distribution.

Using OptiFDTD software, various structures have been designed and simulated in the following. Our objective is to observe the fluctuations of the photonic band gaps sustained by a periodic variation of the effective index along the propagation direction on the SLSW platform. The first and easiest case is the Bragg grating.

### 3.3 Basic Bragg grating structure

As a reminder, the width of the loading strip ($w_p$) is 1.2 $\mu m$ on the top of a horizontal slot waveguide. Also note that only the top polymer strip is structured, and not the horizontal slot waveguide. The refractive index difference between the zone out of the strip and the zone under the strip has been calculated to be $\Delta n = 0.0897$. According to Eq. (2.17), the period of a rectangular Bragg grating as depicted in Figure 3.1 (a), should be $p = 475$ nm in order to expect a photonic band gap centered at $\lambda = 1550$ nm. As a starting point for the other parameters, we set the number of periods to $N = 100$ and the fill factor to $FF = 0.5$. The fill factor is here defined as the ratio of the area without the strip material to the total period.
area. In case of a linear Bragg grating with rectangular features crossing completely the waveguide, it can be expressed as $FF = d/p$.

Figure 3.1: (a) Sketch of a Bragg grating, (b) Transmission spectrum of a SLSW Bragg grating for $N = 100$, $p = 475$ nm, and $FF = 0.5$. A photonic band gap is opened around $\lambda = 1550$ nm.

Figure 3.1(b) represents the photonic band gap that has been obtained for this structure. From the figure, we see that the photonic band gap appears, as expected, at $\lambda = 1550$ nm, with a minimum transmission around 3% at the Bragg wavelength and a full width at half maximum FWHM = 42 nm. The FWHM is defined as the width of the photonic band gap measured at half of its maximum amplitude. We also observe that the photonic band gap does not appear to be symmetric. The left edge of the band gap is not as steep as the right edge. The reason behind this asymmetry will be discussed in more details later. Our main concern, in this section, is the effect on the band gap of the different parameters ($p$, $N$ and $FF$). For this study, each parameter was varied at a time, keeping the two others constant.

3.3.1 Effect of variation of period

The fill factor and the number of periods were kept constant at 0.5 and 100 respectively. The period of the grating was varied from 400 nm to 500 nm with an interval of 5 nm. We observe from the graphs in Figure 3.2, that with the increase of the
period, the photonic band gap shifts to the longer wavelengths. Figure 3.2(a) shows the map of the transmission spectra of the SLSW-based Bragg grating as a function of the period and the wavelength. The dark region on the map represents the region of minimum intensity, i.e., the photonic band gap and Figure 3.2(b) represents the position of the central wavelength as a function of the period. The first figure shows that the overall width and depth of the photonic band gap remains almost constant in the studied period range. The second figure clearly shows that the position of the photonic band gap maintains, as expected, a linear relationship with the period of the grating. The Bragg wavelength shifts linearly to the longer wavelengths with the increasing grating period, with a slope of 3.25 when both the Bragg wavelength and the period are in $nm$. Some of the transmission spectra for different selected periods have been plotted in Figure 3.2(c). The figure clearly shows the shift in the Bragg wavelength of the photonic band gap with the increase in the grating period. Moreover, a closer look at the shape of the photonic band gaps shows, as already observed, that the left edge of the band gaps are steeper at the shorter wavelengths. Whereas, the extinction ratios of the right edge of the band gaps decreases at the longer wavelengths. However, from this Figures 3.2 (a) and (c) one can see that for larger periods, the left edge of the photonic band gap is less and less steep. This means, for wavelength belonging to the air band, an increase of leaking. Indeed, for these wavelengths, light is confined under the low index regions (no strip regions), where light can escape easily from the waveguide. Since we keep the width of the channel waveguide constant it is obvious that for larger period, corresponding to a photonic band gap centered to longer wavelength, the structure is more leaky.
Figure 3.2: Three representation of the variation of the Bragg grating response with the period. Except the period which is varying, all other parameters are fixed: \( N = 100, \ FF = 0.5 \). (a) Map showing in false colour the transmission spectra as a function of the period and the wavelength; (b) Position of the Bragg wavelength with the period; (c) Selected transmission spectra showing the evolution of the shape of the photonic band gap for 5 periods.

3.3.2 Effect of variation of fill factor

Here, we observe the effect on the photonic band gap with the variation of the fill factor, keeping the period and the number of periods constant at 475 nm and 100 respectively. The fill factor was varied from 0.15 to 0.50 with a step of 0.05. The graphs in Figure 3.3 shows the effect on the shape of the band gap with the variation of the fill factor. Figure 3.3(a) shows the map of the transmission spectra through the SLSW structure as a function of the fill factor and the wavelength. The dark region of the map signifies the photonic band gap where the transmission of light is minimum. As this dark region stays almost constant at about 1550 nm, hence we conclude that the Bragg wavelength remains almost constant with the variation of the fill factor. The Bragg wavelength, in this case, decreases linearly with the increasing fill factor. Some transmitted spectra for selected fill factors have been plotted in Figure 3.3(b). The figure depicts the shift as well as the decrease in the transmission of the photonic band gaps with the increasing fill factor. Also, the left edge of the photonic band gaps are steeper with the decreasing fill factor. This is
explained by the fact that more the fill factor increases, more the region without
strip become longer and give space to light to leak out the waveguide.

![Figure 3.3](image)

**Figure 3.3:** Three representation of the variation of the Bragg grating re-
response with the fill factor. Except for the fill factor which is varying, all other
parameters are fixed: \( p = 475 \text{ nm}, N = 100 \). (a) Map showing in false colour
the transmission spectra as a function of the fill factor and the wavelength;
(b) Selected transmission spectra showing the evolution of the shape of the
photonic band gap for 5 fill factors.

### 3.3.3 Effect of variation of number of periods

Next, we observe the effect on the photonic band gap with the variation of the num-
ber of periods. In this case, the number of periods has been varied from 50 to 500
keeping the period and the fill factor constant. Figure 3.4 represents the variation
of minimum transmitted intensity at the photonic band gap with the number of pe-
riods. From the graph, it is evident that with the increase in the number of periods,
the transmission of light at the photonic band gap decreases exponentially. When
the number of periods is at or above 150, the transmission of the photonic band
gap is almost constant at around zero. More the number of period increases more
the strength of the photonic crystal increases. Usually, in conventional integrated
photonicics, increasing the length means increasing the propagation losses. One of our
assumption is that increasing the length of the photonic crystal will not change dras-
tically the losses in our device: Since the structure is strip-loaded, only a very weak
part of the guided mode interact with the loading strip and thus can be subjected to scattering.

![Graph](image)

**Figure 3.4**: Minimum transmission as a function of the number of periods.

### 3.3.4 Discussion of the basic Bragg grating structure

From the results obtained in section 3.3, we may conclude that the shape of the photonic band gap observed for the Bragg gratings changes as expected with the variation of the period, fill factor, and the number of periods. The variation of the period causes a change in the Bragg wavelength. Whereas, the variation of the fill factor and the number of periods mainly effects on the amount of light allowed to transmit through the band gap. If the shape of the band gap is closely observed in Figure 3.1(b), we can see that the left edge is not as steep as the right edge. This corresponds to the confinement of light in the channel strip loaded slot waveguide due to the geometry of the strip. The left edge, also called air band, correspond to wavelength for which light is confined in the low effective index region of the waveguide. This causes a leaking of light in the slab waveguide and leads to a decrease of the transmitted intensity at the output of the waveguide. Note that even though light escapes the channel, it remains guided in the horizontal slot waveguide. The right edge, or dielectric band, correspond to wavelengths confined in the high effective index of the waveguide. This part of light remains well guided in the channel.

The structure is intended to be low loss, and a solution had to be found in order to avoid leakage from the waveguide. Hence, it was necessary to define a novel geometry that will allow a photonic band gap and good confinement of light at the
same time. Three designs are presented in the following sections: 1) the corrugated grating; 2) the row of circular holes; 3) the row of elliptical holes. In all cases, the idea remains the same: to create a modulation of the effective index, without losing the well-guidance of the waveguide for wavelengths surrounding the photonic band gap.

3.4 Photonic crystal structure by periodic corrugation of the strip edges

![Figure 3.5](image)

**Figure 3.5:** (a) Sketch of a photonic crystal with periodic corrugation, (b) Transmission spectrum of a SLSW corrugated Bragg grating for \( N = 1000 \), \( p = 466 \text{ nm} \), and \( FF = 0.5 \). A photonic band gap is opened around \( \lambda = 1553 \text{ nm} \).

First, we study the corrugated grating structure that was designed to obtain a perfectly symmetric band gap. The structure is the loading strip with corrugated edges, i.e., the two parallel edges of the loading strip of the SLSW waveguide are periodically structured with a rectangular pattern [57]. The structure is shown in Figure 3.5(a). To observe a photonic band gap, the parameters of the structure are set to \( p = 466 \text{ nm} \), \( N = 1000 \), and \( FF = d/p = 0.5 \). The refractive index difference between the zone out of the strip and the zone under the strip has been calculated to be \( \Delta n = 0.0897 \). The corrugation widths, \( w_1 \) and \( w_2 \) were designed to be 1.2 µm.
and 1.5 $\mu m$ respectively. The Figure 3.5(b) represents the photonic band gap that was observed at 1553 nm having a FWHM equal to 5 nm. Note that the photonic band gap obtained for this structure appears to be steep at both the band edges.

### 3.4.1 Effect of variation of number of periods

Now, to observe the effect on the photonic band gap with the variation of the number of periods, the period of corrugation and the fill factor were kept constant. The number of periods were then varied from 100 to 1000. The Figure 3.6 represents the variation of the minimum transmission at the Bragg wavelength with the number of periods. It can be observed from the graph that even for a 1000 periods long structure the minimum transmission is still 3%.

![Figure 3.6: Minimum transmission as a function of the number of periods.](image)

### 3.4.2 Discussion of the corrugated Bragg grating structure

Therefore, observing the shape of the photonic band gap in Figure 3.5(b) we may conclude that, the goal of achieving a symmetric band gap was successful. As the propagating light, in this case, did not pass through any low effective index region, light was well confined within the channel strip loaded slot waveguide.

However, one can remark that the strength of the photonic crystal is less than that in the case of the fully patterned Bragg grating (previous section). Figure 3.7 shows the effect of the amplitude of the corrugation ($w_2-w_1$) on (a) the minimal central wavelength of the photonic band gap, (b) the minimal transmission, and (c) the width of the grating. One can immediately see that the position of the photonic band gap and its width depends linearly on the amplitude of the corrugation, and
that the visibility (or depth) of the gap is quadratically linked to this amplitude. This structure offers two advantages compared to the simple Bragg grating: a new degree of freedom for the design and a better field confinement under the loading strip.

Figure 3.7: Effect of the amplitude of the corrugation \((w_2-w_1)\) on (a) the minimal central wavelength of the PBG, (b) the minimal transmission, and (c) the width of the grating.
3.5 Photonic crystal structure with air holes

Next, we design a photonic crystal with circular air holes. This structure can be seen as the “negative” of the corrugated grating. The idea behind this structure is similar to the previous one: opening a photonic band gap without losing the confinement under the strip. The air holes are the regions without the strip material having a lower effective index. The designed structure, as illustrated in Figure 3.8(a), has a period $p = 470$ nm with 150 number of periods ($N$). The radii of the circles are $\frac{1}{2.5^{th}}$ times of the period. Therefore, the fill factor, which in this case is the ratio of the area of the circle to the area under the period is nearly 0.5. The effective index of the holes is 1.6087 and that of the remaining region with the strip is 1.6984.

![Figure 3.8](image)

**Figure 3.8**: (a) Sketch of a circular Bragg grating, (b) Transmission spectrum of a SLSW circular Bragg grating for $N = 150$, $p = 475$ nm, and $FF = 0.5$. A photonic band gap is opened around $\lambda = 1565$ nm.

The photonic band gap obtained for this particular structure, as shown in Figure 3.8(b), is symmetric, but does not appear to be clean. The reason behind this is the insufficient time for the simulation specified to the software. Nevertheless, we obtain the photonic band gap at 1565 nm and the FWHM of the band gap is around 12 nm. It is expected since Eq. (2.17) is just an approximation working well for the rectangular apertures, but having limitations with more complex geometry. Such
a fact is not an issue, because the position of the photonic band gap can be easily shifted by varying the period.

### 3.5.1 Effect of variation of number of periods

Once again, for this structure, we observe the effect on the minimum transmission of the photonic band gap with the increase in the number of periods. Similarly, as in the previous cases, the period of grating and the fill factor were kept constant and the number of periods were increased. From Figure 3.9, it is evident that we obtain zero transmission at the band gap when the number of periods are 300.

![Figure 3.9: Variation of the minimum transmission at the photonic band gap with the increase in the number of periods.](image)

### 3.5.2 Discussion of the circular Bragg grating structure

Thus, we observe symmetric photonic band gaps for the circular gratings, similar to the one obtained for the corrugated gratings in section 3.5. As light propagates through the circular holes (low index region), it tends to leak into the slab waveguide, losing its confinement. But since the low index region is surrounded by the strip materials (high index region), it prevents the light to disperse. As a result, light is well confined in the low index region, as well as the high index region, which corresponds to the air band and the dielectric band respectively. Compared to the corrugated structure, the circular row of holes offer the advantage of a high strength of the photonic crystal, which yield to a shorter structure. Moreover, it is easier to adapt the parameters of the photonic band gap (position and width) because
holes are bigger than the previously mentioned corrugation, relaxing a little bit the fabrication.

### 3.6 Elliptical Bragg grating structure

In this design the circular holes were replaced with elliptical holes. That is, the Bragg grating, in this case, are elliptical in shape. Figure 3.10(a) illustrates the structure of the elliptical grating where the elliptical holes are the regions without the loading strip, having low refractive index. The radius of the ellipse in the direction of the propagation of light ($R_z = D_z/2$) and perpendicular to the propagation of light ($R_y = D_y/2$) are 0.15 µm and 0.6 µm respectively. The designed structure has a grating period ($p$) = 475 nm with 150 number of periods ($N$). The effective index of the ellipse is 1.6087 and that of the remaining region with the strip is 1.6984. Figure 3.10(b) shows the photonic band gap obtained for this structure, where Bragg wavelength appears to be at 1540 nm and the FWHM of the band gap is around 35 nm. One can also observe that the shape of the photonic band gap obtained for this structure is not symmetric.

![Elliptical Bragg grating structure](image)

**Figure 3.10:** (a) Sketch of an elliptical Bragg grating, (b) Transmission spectrum of a SLSW elliptical Bragg grating for $N = 150$, $p = 475$ nm, and FF = 0.5. A photonic band gap is opened around $\lambda = 1540$ nm.
3.6.1 Effect of variation of period

Once again, for this structure, the effect on the band gap with the variation of the period is observed, as done in section 3.3.1. Keeping the number of periods constant at 150, the period is varied from 400 nm to 500 nm at an interval of 5 nm.

![Graphs showing the variation of the elliptical Bragg grating response with the period.](a) Map showing in false colour the transmission spectra as a function of the period and the wavelength; (b) position of the Bragg wavelength with the period; (c) Selected transmission spectra showing the evolution of the shape of the photonic band gap for 5 periods.

**Figure 3.11:** Three representation of the variation of the elliptical Bragg grating response with the period. Except for the period which is varying, all other parameters are fixed: N = 150, FF = 0.5. (a) Map showing in false colour the transmission spectra as a function of the period and the wavelength; (b) position of the Bragg wavelength with the period; (c) Selected transmission spectra showing the evolution of the shape of the photonic band gap for 5 periods.
Figure 3.11(a) shows the map of the transmission spectra of light through the SLSW-based elliptical grating structure, as a function of the period and the wavelength. The dark region in the map shows the region of minimum intensity in the transmission spectra, i.e., the photonic band gap. Figure 3.11(b) shows the position of the photonic band gap as a function of the period. The Bragg wavelength shifts linearly to the longer wavelengths with the increasing grating period, with a slope of 3.33 when both the Bragg wavelength and the period are in nm. Some of the transmission spectra for selected grating periods have been plotted in Figure 3.11(c). The graph clearly depicts the shift of the photonic band gaps to the longer wavelengths with the increase in the grating periods. It is also observed that with the increase in the period, the transmission of the band gap decreases. This is due to the change in the fill factor that takes place with the increase in the grating period. The fill factor, which in this case is the ratio of the area of the ellipse to the area under a period, was initially set to 0.5. But with the increase in the period of the grating, the area under the period increases, whereas the area of the ellipse remains constant. Thus the ratio changes, which in turn changes the fill factor. As a result, it also affects the edges and the FWHM of the photonic band gap. The left band edges are less and less steeper with the increasing grating period which corresponds to the leaking of light at the air band. Whereas, the FWHM of the photonic band gap increases with the increasing grating period. Therefore, from the Figures 3.11(a) and 3.11(c), one can conclude that since the width of the channel waveguide and the radii of the ellipse crossing the channel are kept constant for the larger period, which in turn alters the fill factor, the waveguide structure becomes more leaky.

3.6.2 Effect of variation of number of periods

Now, we observe the effect on the minimum transmission of the photonic band gap at the Bragg wavelength with increasing number of periods. Again as in the previous cases, the grating period is kept constant at 475 nm and the number of periods is increased. Figure 3.12 shows that the transmission of the band gap decreases exponentially with the increasing number of periods and is constant at zero when the number of periods is above 300. Therefore, as the number of period increases, the strength of the photonic band gap increases.
3.6.3 Effect of variation of the radii of the ellipse

Lastly, for this structure, we observe the effect on the photonic band gap with the variation of the major and minor radii of the ellipse. As in the previous cases, the period of the grating, the fill factor and, the number of the periods were kept constant as 475 nm, 0.5 and 150 respectively. $R_y$ and $R_z$ were varied in such a way that the major axis of the ellipse was initially oriented in the direction parallel to the propagation of light (i.e., along $z$-axis and $R_y < R_z$), gradually reducing to form a circle ($R_y = R_z$), and finally to an ellipse with its major axis perpendicular to the direction of the propagation of light (i.e., along $y$-axis and $R_y > R_z$). Figure 3.13 represents the transmission spectra for 5 selected structures. One can observe, as the shape of the ellipse changes (from horizontal ellipse to a circle and finally to a vertical ellipse), the transmission of the photonic band gap reduces and the FWHM of the band gap increases. Also, the shape of the band gap which is perfectly symmetric, and the Bragg wavelength at $\lambda = 1565$ nm remains constant for all the structures. Note that the shape of the band gaps obtained in this case does not match with the one observed in Figure 3.10(b). This is because, for these structures, the elliptical holes (the low index regions) are surrounded by the strip materials (high index regions) which prevents the light from leaking as in the case of the structures with rows of circular holes. Only the strength of the grating is modified. This result, although it was expected, is not completely obvious since the nano-structure is small and its effect on the overall change of the effective index inside the slot waveguide has never been proven earlier.
3.6.4 Discussion of the elliptical Bragg grating structure

Hence for this structure, one can conclude that the effect on the photonic band gap observed with the change in the grating period and the number of periods are similar to that observed in the case of the simple Bragg gratings, as in section 3.3. Moreover, we also observe that the shape of the band gap is asymmetric, as obtained for the open Bragg gratings (Figure 3.1(b)). We do not observe symmetric band gaps in this case as the elliptical holes crossing the channel strip are not surrounded by the high index materials like the circular gratings. As a result, propagating light in this case once again loses its confinement at the low index region, i.e., at the regions of the ellipse.

Thus, from all the above observations in section 3.3, 3.4, 3.5 and 3.6, we can say, a symmetric photonic band gap is observed only for the grating structures which are designed in such a way that the low index regions are bounded by the high index material. Hence, effective index distribution along the waveguide influences the generation of the photonic band gap, and this distribution is affected by the geometry of the loading-pattern.
3.7 Photonic crystal cavity structure

Since, the behaviour of the SLSW structure patterned with gratings of different shapes were observed, it would also be interesting to see its behaviour for a resonant cavity. So, the structure designed and simulated, in this case, is similar to the one examined in section 3.4, with an additional cavity included within the periodic corrugation.

![Diagram of photonic crystal with cavity](a)

![Transmission spectrum](b)

**Figure 3.14**: (a) Sketch of a photonic crystal with cavity, (b) Transmission spectrum of a SLSW corrugated Bragg grating with cavity for \(N = 500\), \(p = 465.5\) nm, and \(FF = 0.5\). The resonance appears around \(\lambda = 1551.7\) nm.

The Figure 3.12(a) represents the structure. The two parallel edges of the loading strip of the SLSW waveguide are periodically structured with rectangular patterns on either side of the cavity. The cavity is a similar rectangular pattern on the two parallel edges of the loading strip. The length of the cavity is equal to the period of the corrugation. Due to the presence of the cavity, we expect to observe a resonance within the photonic band gap. To observe the resonance, the design parameters were set to \(p = 465.5\) nm, \(N = 500\), and \(FF = d/p = 0.5\). The corrugation widths, \(w_1\) and \(w_2\), were set to 1.2 \(\mu m\) and 1.5 \(\mu m\) respectively. The refractive index difference between the zone out of the strip and the zone under the strip has been calculated to be \(\Delta n = 0.0897\). Figure 3.12(b) represents the transmission spectrum of the waveguide structure. From the graph, we observe, that the resonance peak (\(\lambda_{peak}\))
appears at 1551.7 nm and the FWHM of the resonance is 0.16 nm. The Q-factor of the resonance is 9698. The Q-factor, which is expressed as the ratio of the central wavelength $\lambda_{\text{peak}}$ to the FWHM, defines the sharpness of the resonance with respect to the central wavelength. Hence, one can conclude that the inclusion of a cavity within the grating structure can induce a sharp resonance.

### 3.8 Simulation results of the structure fabricated

The previous sections have shown the trends for the different structures where their parameters are varied. After fabrication, the effective indices have been measured. The measured effective indices of the fabricated structure for the regions with and without the loading strip, that has also been used for the following simulations, are 1.717 and 1.631 respectively. The measurement of the effective indices are done with a prism coupler, which is discussed later in chapter 4. The purpose of re-simulating the structures is to determine the response of the finally fabricated structures. Note that because of a lack of time it was not possible to wait for the fabrication. Ideally, the structures can be precisely and completely designed using the experimental parameters.

#### 3.8.1 Photonic band gap for the fabricated Bragg grating

The Bragg gratings with parameters $p = 475$ nm and $\text{FF} = 0.5$ have been fabricated on the SLSW platform for 200, 400, 600, 800 and 1000 number of periods (N). The transmission spectra obtained for these structures are shown in Figure 3.15(a). The Bragg wavelength ($\lambda_B$) of the photonic band gaps for all the structures appear at 1568 nm. The shape of the band gap obtained can be well understood from Figure 3.15(b) which shows the photonic band gap for the Bragg grating with 600 periods. It is well observed from the Figure 3.15(b) that the photonic band gap is not symmetric at both the band edges, similar to the graph in Figure 3.1(b). The reason behind this asymmetry is the low confinement of light in the low index region, as discussed before in section 3.3.4. Moreover, as the number of grating periods increases, the low index regions increases. As a result, the light is even less confined, leading to the spread of the air band. The broadening of the air band with the increasing number of periods is clearly visible from Figure 3.15(a). Therefore, a proper photonic band gap might not be visible for this particular structure, when
characterized.

![Graph showing transmission spectra](image)

**Figure 3.15:** (a) Transmission spectrums of the fabricated Bragg gratings with p=475 nm, FF=0.5 and varying number of periods, (b) Transmission spectrum of the fabricated Bragg gratings with p=475 nm, FF=0.5 and N=600

### 3.8.2 Photonic band gap for the fabricated Corrugated grating

The next structure that has been fabricated is the grating with edge corrugations. The gratings with parameters p = 466 nm and FF = 0.5 are fabricated for 200, 400, 600, 800 and 1000 number of periods. The transmission spectra obtained for these structures have been plotted in Figure 3.16(a). The figure shows that the Bragg wavelength for all the structures appears at 1571 nm. Whereas the FWHM of the band gap is 6 nm, which is also constant for all the structures. Note that the increase in the number of gratings has lead to the decrease in the transmission of light within the photonic band gap keeping the shape of the band gap constant. The Figure 3.16(b) shows the photonic band gap obtained for the grating with 1000 periods. One can observe that the band gap appears to be symmetric at both the edges, as obtained from the simulation in section 3.4. Hence, light is well confined at the low index (i.e., the air band) as well as the high index (i.e., the dielectric band) region. The shape of the band gap matches well with the one in Figure 3.5(b). The shift in the Bragg wavelength occurred due to the change in the effective index, as all the other parameters (p and FF) used for the simulation in section 3.4 matches to the one that is fabricated. Thus, a well defined photonic band gap can be observed for
the characterization of this structure.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{image.png}
\caption{(a) Transmission spectrums of the fabricated Corrugated Bragg gratings with $p=466$ nm, FF=0.5 and varying number of periods, (b) Transmission specturm of the fabricated Corrugated Bragg gratings with $p=466$ nm, FF=0.5 and N=1000}
\end{figure}

\textbf{3.8.3 Photonic band gap for the fabricated Circular Bragg grating}

The third fabricated structure is the circular Bragg grating. The period of grating and the radius of the circle, according to the fabrication, are 470 nm and 190 nm respectively. The structure has been fabricated for 200, 400, 600, 800, and 1000 periods. The Figure 3.17(a) shows the photonic band gaps for the circular Bragg gratings with the varying number of periods. In this case too, the increase in the number of periods causes a decrease in the transmission of the photonic band gap, as expected. The shape of the band gap exactly resembles the one simulated in the section 3.5. The Figure 3.17(b) represents the band gap obtained for 600 periods. The Bragg wavelengths for all the structures appears at 1568 nm whereas, the FWHM of the band gaps are constant at 10 nm. The band gap for the circular gratings are also symmetric due to the good confinement of light. Since the initial simulation results, obtained in section 3.5, corresponds well to those obtained with the fabricated parameters, the photonic band gap is expected to be well observable.
3.8.4 Photonic band gap for the fabricated Corrugated grating with cavity

The final fabricated structure is the corrugated grating with a cavity. As in the previous cases, this structure has also been fabricated for 200, 400, 600, 800 and 1000 number of periods. These periods appears on either side of the cavity with the parameters \( p = 465 \text{ nm} \) and \( FF = 0.5 \). The Figure 3.18(a) represents the transmission spectra of the structures with the varying number of periods. The resonance peak for all the structures appears at 1567.8 nm. Though the extinction ratio of the band gap and the resonance peak initially increases with the increasing number of periods, the sharpness of the resonance decreases for the structure having periods greater than 600. The best resonance is observed for 400 periods which is shown in Figure 3.18(b). The Q-factor of the resonance is 4479. The transmission spectra obtained for these structures corresponds well to the one simulated in Figure 3.7(b). Therefore, it can be concluded that practically, the corrugated cavity structure may exhibit a sharp resonance.
3.8.5 Field distributions of the grating structure

Now that the transmission spectra for the fabricated structures have been estimated, it would also be interesting to see the distribution of the electric field within the structures, in and around the photonic band gap. The $E_x$ field distribution at the $xz$-plane of the fabricated structures are now evaluated using FDTD. Note that the parameters of the structures used for the simulation are similar to those used in section 3.8.

The Figure 3.19(a-c) presents the $E_x$ field distribution at three different wavelengths in the $xz$-plane of the fabricated Bragg grating structure. It is observed to be consistent with the photonic band gap response shown in Figure 3.15(b). The Figure 3.19(a) corresponds to the field distribution at $\lambda = 1473$ nm (i.e., the left of the band gap or the air band). It clearly shows the leaking of light from the low index region into the slab waveguide that results in the spread of the air band in the photonic band gap. Figure 3.19(b), on the other hand, corresponds to the field distribution at $\lambda = 1570$ nm (i.e., at the center of the band gap). The figure, in this case, shows almost no transmission of light, as expected. Further, the field distribution at $\lambda = 1625$ nm (i.e., the right of the band gap or the dielectric band) is shown in Figure 3.19(c). Here light is well confined within the high index region,
leading to a steep dielectric band of the photonic band gap. Light, in this case, is also well guided within the channel strip loaded slot waveguide.

Figure 3.19: Field distributions of the photonic band gap, corresponding to the fabricated grating structures: For the Bragg grating with parameters $p=475$ nm, FF=0.5 and $N=600$, respectively at: (a) left of the band gap at $\lambda = 1473$ nm, (b) center of the band gap at $\lambda = 1570$ nm and (c) right of the band gap at $\lambda = 1625$ nm. For Corrugated Bragg grating with parameters $p=466$ nm, FF=0.5 and $N=600$, respectively at: (d) left of the band gap at $\lambda = 1520$ nm, (e) center of the band gap at $\lambda = 1571$ nm and (f) right of the band gap at $\lambda = 1666$ nm. For Circular Bragg grating with parameters $p=470$ nm, FF=0.5 and $N=600$, respectively at: (g) left of the band gap at $\lambda = 1538$ nm, (h) center of the band gap at $\lambda = 1568$ nm and (i) right of the band gap at $\lambda = 1635$ nm.
The Figure 3.19(d-f) represents the field distributions at the \(xz\)-plane of the fabricated structure. It is observed that the distributions at the three wavelengths match well with the response of the photonic band gap shown in Figure 3.16(b). The Figures 3.19(d) and 3.19(f) represents the field distributions at \(\lambda = 1520\) nm and \(\lambda = 1666\) nm which corresponds to the left band and the right band of the photonic band gap respectively. The two figures clearly shows the confinement of light at the low index region and the high index regions that result in the perfect symmetric photonic band gap. Figure 3.19(e), on the other hand, shows the field distribution at \(\lambda = 1571\) nm that corresponds to the center of the band gap. The figure, in this case, shows almost no transmission of light, as it should be the case within the band gap. Therefore from the three field distributions, it is well observed that, light is well confined and guided within the channel strip loaded slot waveguide.

The field distribution in the \(xz\)-plane of the fabricated structure is presented in the Figure 3.19(g-i). The Figure 3.19(g) shows the field distribution at \(\lambda = 1538\) nm. It corresponds to the air band of the photonic band gap in Figure 3.17(b). The field distribution shows a well confinement of light, which implies to the confinement of light in the low index region. Similarly, the Figure 3.19(i) refers to the field distribution at \(\lambda = 1635\) nm which lies in the dielectric band of the band gap. A good confinement of light is also observed here. This confinement of light in the high index region of the structure leads to the steep dielectric band of the photonic band gap. The Figure 3.19(h) represents the field distribution at the center of the photonic band gap (at \(\lambda = 1568\) nm). As the photonic band gap prevents light to transmit through the structure, the field distribution, accordingly, shows almost no transmission of light.

### 3.9 Discussion

Observing the different structures that have been designed and simulated in sections 3.3 to 3.7, it can be concluded that the fluctuation in the effective index leads to the generation of a photonic band gap. A proper selection of the grating period generates the photonic band gaps at the desired wavelength. Moreover, a proper selection of the fill factor and the number of periods allows the minimum amount of light to pass through the band gap region. Hence, we can obtain the maximum strength of the photonic band gap. If we compare the shape of the band gaps obtained for the
different designed structures, we observe that the band gaps obtained for the simple Bragg grating as in section 3.3 and for the elliptical Bragg grating as in section 3.7 are not symmetric at both the edges. This is because, as light propagates through the waveguide, it confines in the regions having a high effective index (zone under the strip) which yield to the steep dielectric band. Whereas, it loses its confinement in the regions with low effective index (zone out of the strip) which prevents the light to be confined in the channel SLSW. On the other hand, the photonic crystals with corrugation and the photonic crystals with air holes exhibits perfectly symmetric band gap. The propagating light, in this case, does not lose its confinement. This is due to the fact that, the low index regions of the gratings are bounded by the high index region which prevents the light to escape the SLSW channel. This phenomenon is clearly visible in Figure 3.19.

Comparing these simulations to those performed with the fabricated parameters of the gratings and the measured effective indices in section 3.8, it is observed that the shape of the photonic band gaps obtained for the structures corresponds well. Note that, most of the photonic band gaps observed for the fabricated structures appears to be at around 1570 nm. Since the spectral range of the ASE source used for the characterization is from 1525 nm to 1575 nm, hence a clear photonic band gap might not be observed for all the structures.
In this chapter, we will discuss about the fabrication procedures of the SLSW sample and the prism coupler measurements of the final structure obtained after fabrication. The fabrication of the sample was completed by MSc Ségolène Pélisset. The simulations have been repeated with the measured effective indices and are compared with the results obtained from the characterization.

4.1 Atomic layer deposition

The SLSW structure consists of thin layers of titanium dioxide and silicon dioxide on an oxidized silicon wafer. The atomic layer deposition (ALD) is a popular technique for depositing thin films of various materials with an atomic layer precision. This process has a great importance in industry and research and hence it is used for fabricating our structure.

The ALD process deposits consecutive layers of thin films by exposing the surface to gases. It sends alternate pulses of gaseous chemical precursors into the reactor where the substrate is placed. This pulse is generated for a finite time period so that the precursors can react well with the substrate of the surface which in turn produces a monolayer. Thereafter, the unreacted precursors and by-products remaining within the reactor are purged by nitrogen. Once the chamber is purged, the second precursor is pulsed within the chamber which reacts with the first. Finally, the reactor is again purged. Thus we obtain a layer of the material on the substrate. Now, this process is repeated in a cycle to achieve the desired thickness of the layer. The Figure 4.1 describes the steps of the ALD.
Figure 4.1: The working principle of ALD. (a) Pulsed of the first precursor, (b) Purging of the remaining precursors, (c) Pulse of second precursor, (d) Purging of the remainder.

During the process, a pressure of 2 to 3 mBar should be maintained within the reactor. This pressure within the reactor is maintained by controlling the flow of nitrogen. Whereas, the pressure in the chamber surrounding the reactor should be higher, at 5 mBar to prevent the leaking of the precursors from the reactor.

Figure 4.2: The Beneq TFS 200 ALD equipment used for the construction of SLSW.
The sample is placed on a plate within the reactor which is heated to 120° C for the deposition of TiO$_2$ and 150° C for SiO$_2$. The precursors used for TiO$_2$ are titanium tetra-chloride (TiCl$_4$) and water (H$_2$O) and that used for SiO$_2$ are oxygen (O$_2$) and the other is under patent and hence confidential. Moreover, the deposition of SiO$_2$ requires plasma enhancement. Figure 4.2 represents the ALD equipment that has been used for this work.

4.2 Spin coating

After the deposition of the slot waveguide layers, we proceed to fabricate the strip on the slot waveguide. This can be obtained by spin coating. This technique is used widely since it can efficiently produce thin films on the substrate.

![Figure 4.3: Working principle of a spin coater.](image)

First, the substrate to be coated is placed on the vacuum chuck which holds it in place. The diluted photoresist is then added manually with the help of a syringe to the center of the substrate, which then starts rotating. As a result, the solution spreads evenly on the substrate due to the applied centrifugal force. As the spinning continues, some of the solution flowing towards the edges is shoved off the substrate. This spinning is continued until the desired thickness of the layer is achieved. Figure 4.3 describes the steps for the spin coating technique. The speed, as well as the duration of the spinning, determines the final thickness of the film developed.
4.3 Electron beam lithography

To finalize the SLSW device, the sample is exposed to electron beam lithography for patterning the various structures that have to be characterized. The electron beam lithography, also known as the e-beam lithography uses a focused beam of electrons to imprint the pattern on the sample. The layer of the sample exposed to the e-beam is the photoresist. The incident electrons change the solubility of the resist. This allows the removal of the resist material either from the region exposed to the beam when cleansed with the developer. Thus the pattern is obtained. Electron beam lithography is advantageous over optical lithography as it can pattern structure with higher resolution ranging from micrometers to a few nanometers.
Figure 4.5: Electron beam lithography when applied on a sample with negative resist.

With the application of the e-beam lithography on the SLSW structures, it was possible to pattern different types structure on the same sample. The structures include a series of the Bragg gratings, the corrugated Bragg gratings, the corrugated Bragg gratings with a cavity and circular Bragg gratings.

Therefore, the entire process of the fabrication of the structure that has been followed can be summed up in the following steps.

- Soft cleaning of the fused silicon wafer (for prism coupler measurements) with acetone and ultra-sound for 3 minutes and finally rinsing the sample with isopropanol.
- Oxygen plasma cleaning of the oxidized silicon wafer.
- Atomic layer deposition of TiO$_2$ which forms the lower rail of the slot waveguide.
- Plasma enhanced atomic layer deposition of SiO$_2$ which forms the slot region.
- Atomic layer deposition of TiO$_2$ which forms the upper rail of the slot waveguide.
- Spin coating of the negative resist AZ® nLOF 2070, which forms the loading strip on the slot waveguide.
- Pre-baking of the SLSW to evaporate the excess solvent of the resist.
- Electron beam lithography for patterning the structures on the oxidized silicon wafer.
• Post-baking of the sample.

• Finally, development of sample with pure AR 300-47 developer for 90 seconds and rinsing with UltraPure water for 30 seconds. Followed by drying with nitrogen blowing and 15 minutes of heating in convective oven at 50°C to complete the drying.

4.4 Fabricated structure

Figure 4.6: SEM images of the cross-section of (a) the slot region and (b) the strip loaded slot region.

In order to examine the structure, Scanning Electron Microscope (SEM) images of the sample have been taken. In order to do this, the residue pieces of the original sample after cleaving were imaged. The Figure 4.6 (a) represents the SEM image of the cross-section of the slot region of the SLSW structure. The picture shows ALD deposited layers of the lower rail (TiO₂), the slot (SiO₂) and the upper rail (TiO₂) on the oxidized silicon wafer. Figure 4.6 (b) on the other hand, represents the cross section of the slot region of the SLSW structure along with the loading strip.

The grating patterns on the SLSW structure obtained with the help of e-beam could not be imaged. To image an object with SEM, the object should be coated with a conducting layer such as gold or copper. This layer of the conducting material can change the absorption property of the material even when it is removed. As a result, the fabricated structures may not behave as predicted with the help of FDTD.
This was not a problem for the cross-sectional image of the slot and the strip loaded slot region as a residue piece of the cleaved sample was coated with gold to obtain the SEM image.

The thickness of all the layers of the final structure was measured with an Ellipsometer. The thicknesses obtained from the measurements are, $t_b = 184.7 \pm 0.3 \mu m$, $t_s = 76 \pm 0.5 \mu m$, $t_u = 196.6 \pm 0.2 \mu m$ and the thickness of the oxidised silicon layer is $3030.9 \pm 0.4 \mu m$. The thickness of the polymer layer was verified with the Stylus Profilometer and the resultant thickness was 249 nm. The effective indices were verified after the deposition of the slot waveguide and the strip loaded slot waveguide with the help of the prism coupler, discussed below.

### 4.5 Prism coupler

![Prism coupler diagram](image)

**Figure 4.7**: Sketch of the prism coupler.

Thin film dielectric waveguides used in integrated optics are characterized by the film thickness and the refractive index of the film. The prism coupler provides an efficient technique to measure these parameters. A sketch of the prism coupler is shown in figure 4.7. The dielectric waveguide to be measured is placed against the base of the prism, such that a thin air gap is trapped between the waveguide and the prism. Light from the laser source is then incident on the prism in such a way that it is reflected from the base of the prism. The evanescent field of the light in the prism couples with the modes of the dielectric waveguide within the small air
gap. The light makes an angle $\theta_p$ with normal to the base of the prism, as shown in Figure 4.7. This angle is then varied until light is no more reflected from the base of the prism and is guided through the waveguide. The coupling, in this case, excites a mode within the film.

The propagation constant of the mode can be determined by the following equation [58],

$$\beta = k_0 n_{prism} \sin \theta_p$$  \hspace{1cm} (4.1)

where, $k_0 = \omega/c$, $\omega$ is the angular frequency of light and $c$ is the velocity of light. $n_{prism}$ is the refractive index of the prism and $\theta_p$ is the angle of incidence. The prism coupler measures the reflected intensity with respect to the angle, which is later converted to the effective index ($n_{eff}$). The relation between the propagation constant $\beta$ and the effective index is given as [59],

$$\beta = n_{eff} \frac{2\pi}{\lambda}$$  \hspace{1cm} (4.2)

It is possible to excite TE and TM modes within the film. When only one mode is observed, either the thickness or the refractive index of the film has to be known to calculate the other.

In our case, we were interested only on the effective index measured with such a method. So, the effective index of the slot waveguide and that of the strip loaded slot waveguide has been measured with the use of the prism coupler. Also, the change in the effective index with the variation of the thickness of the loading strip has been studied.

### 4.5.1 Effective index measurements

The prism coupler setup was used to measure the effective indices of the slot region and the strip loaded slot region, after the deposition of the layers by ALD and spin coating respectively. These measured values were used in the simulations in section 3.8. The effective indices, as shown in Figure 4.7, were measured at $\lambda = 1547$ nm. The figure represents the reflected intensity with respect to the effective index for the slot region (solid line) and the strip loaded slot region (dashed line). The dip in the intensity appears when light is guided through the waveguide. The tip of the dips corresponds to the $n_{eff}$ of the guided mode. Since we set the polarization of
the light to TM, we observe one mode for both the regions. Therefore the modes represent the fundamental TM mode in each case.

![Graph](image)

**Figure 4.8**: Variation of the reflected intensity with respect to the incident angle (transformed here into effective index for a direct reading of the interesting value) for the slot waveguide (after ALD and before spin coating of nLOF) and for the strip loaded slot waveguide (after spin coating of nLOF).

<table>
<thead>
<tr>
<th>Waveguide region</th>
<th>Calculated $n_{\text{eff}}$</th>
<th>Measured $n_{\text{eff}}$</th>
<th>Recalculated $n_{\text{eff}}$ with measured thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slot</td>
<td>1.6087</td>
<td>1.631</td>
<td>1.6261</td>
</tr>
<tr>
<td>Strip loaded slot</td>
<td>1.6984</td>
<td>1.717</td>
<td>1.7107</td>
</tr>
</tbody>
</table>

**Table 4.1**

Comparison between the calculated and measured effective indices in the slot and the strip loaded slot region of the waveguide.

If the effective indices calculated with FMM are compared with those measured with the prism coupler (Table 4.1), we see that the deviation is about 1.4% for the slot region and about 1.1% for the strip loaded slot region. Whereas, if the effective indices, re-calculated with the measured thickness of the slot and the strip loaded
slot waveguide are compared to those obtained from the prism coupler, we see that the deviation is about 0.30 % and 0.36 % for the slot and the strip loaded slot region respectively.

Though the deviation in the effective index is small, but this change causes a shift in the Bragg wavelength of the photonic bandgap. The effect is visible when the simulation results obtained in the first place are compared to those simulated with the measured effective indices (chapter 3).

Next, we observed the change in the effective index with the variation of the thickness of the polymer AZ-nLOF-2070. This measurement was also performed for \( \lambda = 1547 \) nm. For each measurement, after spin coating, the sample was pre-baked at 110\(^0\) C for 60 s. This solidifies the resist without curing it. The spinning speed to achieve a desired thickness of the resist was determined from a relation between the speed of rotation of the spin coater and the thickness of the resist. Once the sample was prepared, the effective index of the sample for that particular thickness of resist was measured. After the measurement, the sample was developed in pure AR-300-47 for 90 s and then rinsed in deionized water for 30 s to remove the developer completely. The sample is then prepared to be spin coated for another thickness of resist. The effective index of the sample without the resist layer was checked in between the measurements to verify that the ALD layers were not affected by the development.

Table 4.2

<table>
<thead>
<tr>
<th>Thickness in nm</th>
<th>TM(_0)</th>
<th>TM(_1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>181</td>
<td>1.70161</td>
<td></td>
</tr>
<tr>
<td>262</td>
<td>1.71716</td>
<td></td>
</tr>
<tr>
<td>294</td>
<td>1.72135</td>
<td></td>
</tr>
<tr>
<td>439</td>
<td>1.73278</td>
<td></td>
</tr>
<tr>
<td>823</td>
<td>1.74152</td>
<td>1.46757</td>
</tr>
<tr>
<td>1404</td>
<td>1.74214</td>
<td>1.52090</td>
</tr>
<tr>
<td>1711</td>
<td>1.74090</td>
<td>1.54039</td>
</tr>
</tbody>
</table>
The effective indices of the TM modes measured for the various thicknesses of the resist have been listed in Table 4.2. The result shows the presence of more than one mode for the greater thicknesses of the resist. The Figure 4.8 shows the reflected intensity with respect to the effective index for some of the resist thicknesses listed in the table. The figure shows that the effective index of the modes increases with the increase in the resist thickness. Therefore, a proper thickness of the resist must be chosen to obtain the desired effective index of the fundamental TM mode.

### 4.6 Preliminary experiment

A preliminary experimental result has been obtained by the characterization of one of the fabricated structures: the row of holes. The characterization setup, depicted in Figure 4.10, is composed of an Amplified Spontaneous Emission (ASE) source generating light around $\lambda = 1550 \text{ nm}$ over an about 50 nm broad spectral range. The source is amplified with an Erbium Doped Fiber Amplifier (EDFA) and the polarization is set with a polarizer and a polarization controller. TM polarization must be injected into the SLSW nano-structure. The injection in the waveguide is performed using a tapered lens fiber mounted on an XYZ translation stages controlled with piezo-actuators having a resolution step of about 30 nm. The collection
is either performed using another lens fiber connected to an Optical Spectrum Analyzer (OSA) or with an optical microscope, imaging the output of the waveguide on an infrared camera.

![Schematic diagram of the setup used to characterize the structure on SLSW.](image)

**Figure 4.10**: Schematic diagram of the setup used to characterize the structure on SLSW.

While characterizing the sample, we remarked a small variation in the structure parameters. The spectra are then expected to be shifted compared to the simulation. These differences occurred during the fabrication: the thicknesses of the layers deposited by ALD are slightly different, the patterns done by e-beam lithography have minor fluctuations, and the nLOF resist thickness might be a bit different than the one used for the simulations. These differences have been measured too late in the fabrication process and after redoing the simulation (see chapter 3) we remarked that most of the photonic band gap is expected to be outside of the spectral range of the source ($\lambda > 1575$ nm). However, since very slight modifications can induce so big changes in the response of our devices, one may expect some reverse effect. We observed the spectrum of a 200 period long photonic crystal composed of one row of holes. The experimental spectrum is presented in Figure 4.11. One can see a very sharp and deep photonic band gap centered at $\lambda = 1554.5$ nm. The extinction ratio is about 11 dB, which is more than enough in most of integrated optics applications. One can remark a thinner photonic band gap also. Compared to the simulation, one
can see many differences. This is under investigation.

![Transmission spectrum of the circular Bragg grating structures on SLSW platform.](image)

**Figure 4.11:** Transmission spectrum of the circular Bragg grating structures on SLSW platform.

This first result is promising. However, a new sample is under fabrication in order to check all the other structures. The most important advantage of the SLSW platform, besides the low-loss potential, is the fact that effective indices can be measured before the patterning. We did not use this privilege because of a lack of time. The work is in progress and a paper, in preparation, will be terminated after the characterization of the new sample.

### 4.7 Discussion

The first part of the chapter describes the techniques that have been used to fabricate the SLSW sample. The ALD process used to fabricate the layers of the slot waveguide is widely used for the deposition of homogeneous thin films of different materials. It allows a well controlled thickness deposition of the films with atomic layer precision. On the other hand, the spin coating process used to deposit the
polymer layer is advantageous due to the simplicity of the technique. The process allows thin and uniform deposition of the film on the substrate. Moreover, the fast spinning speed leads to a high air flow which causes fast drying. As both techniques are widely used in industries, it permits a mass production of the sample. Horizontal slot waveguides are extremely sensitive to the surface roughness at the interfaces between the layers. So, the ALD method used to deposit the layers is useful as it produces smooth layers minimizing the losses.

The second part of the chapter deals with the effective index measurements with a prism coupler. The purpose of the measurement was to determine the effective indices of the slot and the strip loaded slot regions of the fabricated SLSW waveguide. The measured values were compared to those calculated with FMM. The deviation observed between the calculated and experimental result was around 1% in both the cases. Nevertheless, the effective index of the propagating fundamental TM mode proves the confinement of light in the transverse direction within the slot. Lastly, the prism coupler measurements performed for the different polymer thicknesses give us an idea about the change of the effective index of the modes due to the varying thickness. The results in Table 4.2 gives us an idea of the presence of an additional mode within the waveguide when the thickness off the polymer is high (823 nm, 1404 nm, 1711 nm). Therefore, to obtain a single mode waveguide, the thickness of the polymer should be minimized.

Lastly, a preliminary result of the characterization of one of the fabricated structures has been presented. The transmission spectrum for the circular Bragg grating with 200 periods is presented in Figure 4.11. The result shows a sharp and deep photonic band gap centered at \( \lambda = 1554.5 \) nm. Compared to the simulation, many differences in the obtained result can be observed. The reason behind this fluctuation could not be determined due to the lack of time. The work is in progress.
Chapter V

Conclusions

The purpose of this master thesis was the investigation of a patterning on the strip-loaded slot waveguide platform. We focused mainly on the Bragg grating structure and evaluate the influence of geometrical variations on the response of the SLSW, which is a low index contrast waveguide.

Bragg gratings were designed and simulated on the SLSW samples using the Finite Difference Time Domain (FDTD) software. The parameters of the SLSW platform used for the design of the waveguide were optimized in a previous work [20] and the effective indices used for the simulations were calculated using Fourier Modal Method (FMM) and further measured, after fabrication, with the prism coupler technique. It was observed from the simulation results that the fluctuation in the effective index leads to the generation of a photonic band gap. Initially, a basic rectangular Bragg grating was simulated (section 3.3). The photonic band gap obtained for this design was asymmetric in shape. The asymmetry observed at the right edge (which corresponds to the air band) was due to the loss of light confinement in the low index region. Although light escaping from the channel waveguide remains confined in the horizontal slab slot waveguide, this spreading of the mode leads to a decrease in the transmission at the output of the waveguide.

On the other hand, the right edge (which corresponds to the dielectric band) was steep due to the confinement of light in the high index region. To overcome the asymmetry at the air band, three other structures were investigated. The first structure was a grating, created by a corrugation of the side walls of the loading-strip (section 3.4). The photonic band gap obtained in this case was symmetric due to the confinement of light in the low index as well as the high index region.
Similar symmetric photonic band gap was also observed for the gratings with circular holes (section 3.5). Whereas, the photonic band gap obtained for the gratings with elliptical holes (section 3.6), was not symmetric at both the band edges. Therefore, the study of the different grating structures shows that even with a low contrast waveguide and low contrast nano-structure, a symmetric photonic band gap can be obtained. The effective index distribution along the waveguide is the key point in the study, and this distribution is, obviously, affected by the loading-pattern. The high index region, in this case, prevents light to leak out of the channel SLSW. The effect on the band gap with the varying period, fill factor and number of periods were also studied. It was observed that the Bragg wavelength shifts to the longer wavelengths with the increase in the grating period. Whereas, an increase in the fill factor and the number of gratings causes a decrease in the minimum transmission at the photonic band gap. The effect of a resonant cavity on the SLSW platform was also examined (section 3.7). A sharp resonance with a Q-factor = 9698 was observed in this case.

The structures were re-simulated (section 3.8) with the fabricated parameters (grating period, fill factor and number of periods) and the measured effective indices (prism coupler measurements). The transmission spectra of the fabricated structures observed, in this case, corresponds well to the results obtained in the initial simulations. The photonic band gap observed for the simple Bragg grating appeared to be asymmetric as light loses its confinement in the low index region. Whereas a perfect symmetric band gap was observed for the gratings with side wall corrugation and circular holes. On the other hand, a resonance with a Q-factor of 4479 was observed for the corrugated grating with a resonant cavity. Though a good match in the shapes of the photonic band gaps were observed, there was a shift in the Bragg wavelength. The reason behind this shift was due to the change in the grating period and the effective indices of the fabricated sample.

The processes used to fabricate the sample were also described. Atomic Layer Deposition (ALD) and spin coating allow deposition of homogeneous and smooth layers of the films of desired thickness on the substrate. The smooth layers at the interfaces of the different film minimizes the losses. Hence, these techniques were used to fabricate the layers of the slot waveguide and the polymer layer on the top of the slot respectively. Electron beam lithography was used to pattern the grating structures on the SLSW sample.
The fabricated sample was then measured with a prism coupler to determine the effective indices of the slot and the strip loaded slot region and also to observe the effect on the effective index with the variation of the polymer thickness. The measured effective indices for the two regions showed a good match with the calculated indices. The measurements of the effective indices of the fundamental TM modes in both the regions proved the transverse confinement of light in the slot. The presence of an additional mode along with the fundamental mode was observed with the increasing thickness of the loading strip.

The characterization of one of the fabricated structures was performed. The transmission spectrum obtained for the circular Bragg grating structure with 200 grating is presented in the thesis. The experimental result did not show a good agreement with the simulated result. However the photonic band gap observed, in this case, was sharp with an extinction ratio of 11 dB which can be useful for the integrated optics applications.

Therefore, from the study, one can conclude that the fluctuation of the effective index on the SLSW platform is advantageous in the field of integrated optics with a wide variety of application in sensing and telecommunication.


