Modeling, Fabrication, and Characterization of a Bragg Slot Waveguide with a Cavity

by

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A thesis submitted in conformity with the requirements for the degree of Master of Applied Science
Graduate Department of Electrical and Computer Engineering
University of Toronto

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Abstract

This thesis encompasses a theoretical analysis, the fabrication, and optical characterization of a novel compact Bragg Slot Waveguide with a Cavity (BSWC). Strong light confinement in the low refractive index slot region formed by two silicon slabs on a silicon dioxide substrate [1] makes this structure useful for optofluidic, sensing, and optical trapping applications. The transmission spectrum of the BSWC can be engineered through the dimensional variations of the waveguide and through the refractive index change of the surrounding medium. BSWC is compact and can be integrated with various components on a chip for increased functionality.

The results in this thesis show a good agreement between analytical and experimental results, while emphasizing the increasing importance of atomic-scale imperfections as a result of fabrication on the nano-scale. The impact of the slot width, slab width, and the cavity length on the waveguide transmission spectrum is investigated.
Acknowledgments

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<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>APTES</td>
<td>Aminopropyltriethoxysilane</td>
</tr>
<tr>
<td>BSW</td>
<td>Bragg slot waveguide</td>
</tr>
<tr>
<td>BSWC</td>
<td>Bragg slot waveguide with a cavity</td>
</tr>
<tr>
<td>CMOS</td>
<td>Complementary metal–oxide–semiconductor</td>
</tr>
<tr>
<td>CATS</td>
<td>software trademark of Synopsys for mask data preparation</td>
</tr>
<tr>
<td>DI</td>
<td>Deionized water</td>
</tr>
<tr>
<td>DL</td>
<td>Detection limit</td>
</tr>
<tr>
<td>EBL</td>
<td>Electron Beam Lithography</td>
</tr>
<tr>
<td>EDFA</td>
<td>Erbium doped fiber amplifier</td>
</tr>
<tr>
<td>FSR</td>
<td>Free spectral range</td>
</tr>
<tr>
<td>HF</td>
<td>Hydrogen fluoride</td>
</tr>
<tr>
<td>IPA</td>
<td>Isopropanol</td>
</tr>
<tr>
<td>IR</td>
<td>Infra-red</td>
</tr>
<tr>
<td>LOC</td>
<td>Lab-On-a-Chip</td>
</tr>
<tr>
<td>MIBK</td>
<td>Methyl isobutyl ketone</td>
</tr>
<tr>
<td>MSDS</td>
<td>Material safety data sheets</td>
</tr>
<tr>
<td>OSA</td>
<td>Optical spectrum analyzer</td>
</tr>
<tr>
<td>PBC</td>
<td>Polarizing beam cube</td>
</tr>
<tr>
<td>PML</td>
<td>Perfectly matched layer</td>
</tr>
<tr>
<td>PMMA</td>
<td>Polymethyl methacrylate</td>
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<tr>
<td>RI</td>
<td>Refractive Index</td>
</tr>
<tr>
<td>RIE</td>
<td>Reactive Ion Etching</td>
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<tr>
<td>RIU</td>
<td>Refractive index unit</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<td>--------------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning Electron Microscopy</td>
</tr>
<tr>
<td>SLD</td>
<td>Superluminescent diode</td>
</tr>
<tr>
<td>SOI</td>
<td>Silicon-on-Insulator</td>
</tr>
<tr>
<td>TE</td>
<td>Transverse electric</td>
</tr>
<tr>
<td>TM</td>
<td>Transverse magnetic</td>
</tr>
<tr>
<td>3D-FDTD</td>
<td>Three-dimensional finite-difference time-domain</td>
</tr>
<tr>
<td>n</td>
<td>Refractive index of a material</td>
</tr>
<tr>
<td>cm</td>
<td>centimeter</td>
</tr>
<tr>
<td>nm</td>
<td>nanometer</td>
</tr>
<tr>
<td>µm</td>
<td>micrometer</td>
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<tr>
<td>mm</td>
<td>millimeter</td>
</tr>
<tr>
<td>fM</td>
<td>femto-Molar</td>
</tr>
<tr>
<td>dB</td>
<td>decibels</td>
</tr>
<tr>
<td>kV</td>
<td>kilovolts</td>
</tr>
<tr>
<td>nA</td>
<td>nano amperes</td>
</tr>
<tr>
<td>µC</td>
<td>micro coulombs</td>
</tr>
<tr>
<td>W</td>
<td>Watts</td>
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<tr>
<td>mT</td>
<td>millitorr</td>
</tr>
<tr>
<td>sccm</td>
<td>Standard cubic centimeters per minute</td>
</tr>
<tr>
<td>λ</td>
<td>Wavelength</td>
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Chapter 1 Introduction

1.1 Overview

Silicon waveguides are rapidly becoming the platform of choice for a range of integrated optical applications. Silicon offers a low propagation loss and is transparent in the near-infra red (IR) range of the optical spectrum, making it a suitable material for use in the near-IR optics and for telecommunications. Light can be strongly confined and efficiently guided in a silicon waveguide when a high-refractive index contrast core and cladding are used; this can be achieved by a low refractive index substrate such as silicon dioxide, forming a Silicon-on-Insulator (SOI) platform. SOI waveguides have found many applications in the fields of biophotonics and biosensing, and especially as transducers for lab-on-a-chip (LOC) applications [2]. Photonic LOC platforms present the advantage of a small device size as a result of the integration of the miniature components on a single chip. Miniaturization leads to high analytical throughput and robust sample processing, while requiring very small volumes of analyte and very little energy. Numerous optical components must be integrated and optimized on a single chip for a truly LOC standalone device: analyte handling and delivery, a functionalized transducer to detect a specific target, as well as the optical source and the optical signal processing.

Various waveguide geometries have been proposed and explored as a transducer for photonics sensing applications, such as ring resonators [3, 4], integrated interferometers [5], photonic crystals [6], and slot waveguides [7], among others. These structures can be used in the label-free sensory applications which detect a shift in the refractive index of the cover medium which results from the changes in the composition or concentration of the cover medium. A field of optofluidics [8] lies not far from photonics sensing as it can utilize the same waveguide properties and combine photonics and fluids in a single platform. This thesis explores a slot waveguide with Bragg corrugations and a cavity with a focus on optofluidic and sensing applications. A novel and promising area of application for slot waveguide structures is in optical trapping. The advantage of slot waveguide optical trapping over more conventional optical tweezers lies in the ability to trap very small dielectric matter [9]. Optical trapping,
release, and propulsion of dielectric particles down to 50 nm in diameter along a 100 nm slot has been demonstrated experimentally [10].

1.2 Thesis Outline

This thesis is organized as follows:

Chapter 2 goes over the background for the slot waveguide concept. It also provides an overview of the major areas of application for slot waveguide structures: optical biosensors, optofluidic filters, and optical trapping.

Chapter 3 summarizes the numerical analysis done in this work. The Bragg slot waveguide with a cavity (BSW) designs are introduced here along with the geometrical parameters which were considered in the design and optimization.

Chapter 4 details the fabrication steps taken to make the waveguide. Measures taken to improve the pattern quality of the fabricated waveguide are presented and discussed.

Chapter 5 presents the results of the characterization experiments for BSWC waveguide. The effects of changes in the slot width, slab width, and cavity length on the transmission spectrum are discussed. The performance of the fabricated waveguide is characterized through RI sensitivity, detection limits, free spectral range (FSR) analysis, and propagation loss.

Chapter 6 deals with suggestions for the future work to improve the BSWC waveguide performance and broaden the spectrum of potential applications.

Chapter 7 concludes the thesis and summarizes the results.
Chapter 2 Background and Literature Review

2.1 Slot Waveguide

The slot waveguide was first proposed by Michal Lipson at Cornell University [1] for enhancing and confining light in a nanometer-scale material with low refractive index. It was shown that the light intensity in the air slot can be up to 20 times higher than in conventional rectangular waveguides utilizing the same materials. Further sections describe the slot waveguide in greater detail.

2.1.1 Slot Waveguide Geometry

A typical slot waveguide consists of two slabs of higher refractive index material, such as silicon (n = 3.478), and lower refractive index material, such as air (n = 1.00) or water (n = 1.333), which form a slot in between the two slabs as shown schematically in Fig. 2.1. The slot waveguide eigenmode is formed by the interaction between the fundamental eigenmodes of the two individual slabs.

![Fig. 2.1 Schematic diagram of the slot waveguide geometry. Slab width \( w_{slab} \), slab height \( h_{slab} \), slab refractive index \( n_{slab} \), slot width \( w_s \) and slot refractive index \( n_s \) are defined.](image)

The field intensity is high inside the slot when the two slabs are closer than the characteristic decay length of each slab [1]. In practice such waveguide can be realized on a Silicon-on-Insulator (SOI) platform, which provides low refractive index (n = 1.44) SiO\(_2\) cladding for better confinement of light close to the device surface [11]. The SOI platform also offers lower material cost compared to silicon nitride or gallium arsenide platforms for example, and offers
optimum compactness as a result of the high core-cladding refractive index contrast [12]. It can be readily integrated with other photonics and optoelectronics components on chip for robust and efficient fabrication.

2.1.1.1 Slot Waveguide Mode

The guiding of the light in the low refractive index core is a result of an imperfect spatial confinement of light by total internal reflection [6]. As a result of very high refractive index contrast at the boundary, the component of the electric field normal to the air/silicon interface experiences a large discontinuity at this boundary, the light intensity being significantly higher in air very close to the interface. To satisfy Maxwell’s equations (1), (2) and (3) below, the electric field must undergo a discontinuity at the high refractive index contrast boundary in order to satisfy the continuity of the normal component of the electric displacement flux density $D$ [1]:

\[ D_S^N = D_H^N \]  

\[ \varepsilon_S E_S^N = \varepsilon_H E_H^N \]  

\[ n_S^2 E_S^N = n_H^2 E_H^N \]

where $E$ is the electric field, $\varepsilon$ is the relative permittivity of the material, $n$ is the refractive index, the subscripts $S$ and $H$ stand for “slot” and “high” refractive index regions respectively, and superscript $N$ represents the components of $E$ and $D$ normal to the material interface. For the high refractive index contrast at the boundary, $n_S \ll n_H$, the electric field in the slot region must be significantly higher than in the higher refractive index region, $E_S^N \gg E_H^N$.

When two such high refractive index silicon slabs are brought sufficiently close to each other forming a slot in between, the two discontinuities interact forming an eigenmode in between the two slabs in the low refractive-index air (Fig. 2.2).
The quasi-transverse electric (TE) mode provides a high confinement factor of 60-70%, while the quasi-transverse magnetic (TM) mode provides only 40-50% confinement factor [13], defined as:

\[ \Gamma_c = \frac{n_c \int_C |E(x,y)|^2}{n_{eff} \int_\infty |E(x,y)|^2} \]  \hspace{1cm} (4)

where C is the cover medium region including the slot region, E is the electric field vector, and x and y are the transverse coordinates.

### 2.1.1.2 Characterizing Performance

The performance of slot waveguide based sensors is typically characterized by the homogeneous sensitivity \(S_h\), the refractive index sensitivity \(S_{RI}\) expressed in nm/RIU, and the detection limit \(DL\) expressed in RIU [14]. The homogeneous sensitivity is defined as the change in the effective...
refractive index of the guided mode with the change in the refractive index of the cladding (the sample) [15]:

\[ S_h = \frac{\partial n_{\text{eff}}}{\partial n_{\text{cladding}}} \]  

(5)

The refractive index sensitivity is defined as the change of the resonant wavelength \( \lambda \) with the change in the RI of the sample [14]:

\[ S_{RI} = \frac{\partial \lambda}{\partial RI} \]  

(6)

The detection limit is defined in terms of the sensitivity \( S_h \) in nm/RIU and the resolution \( R \) in nm [14], which represents the smallest refractive index change which is possible to measure using a given equipment:

\[ DL = \frac{R}{S_{RI}} \]  

(7)

In this project the slot waveguide is formed on an SOI platform with 340 nm top layer of silicon. SOI slot waveguide is compatible with highly integrated photonics technology and can be modeled, fabricated, and characterized using well-established techniques. Si/SiO\textsubscript{2} platform was chosen because it provides a higher refractive index contrast system compared to Si\textsubscript{3}N\textsubscript{4}/SiO\textsubscript{2} which results in stronger confinement of the electric field in the slot region [7]. On the other hand, higher refractive index contrast platform makes the fabricated device more sensitive to small variations in device dimensions and surface roughness. Also, a narrower slot width is required to achieve significant confinement which poses a certain difficulty in introducing fluids into the slot region which have a relatively high surface tension, such as water (71.97 dynes/cm [16]), whereas fluids with lower surface tension are likely to penetrate into the narrow slot region. For example, Barrios et al [17] reported suggestive evidence of isopropanol (surface tension of 21.70 dynes/cm [16]) successfully penetrating the slot region at ambient conditions.

2.1.2 Tunability of the Transmission Spectrum

Slot waveguides are very sensitive to changes in the refractive index of the lower index slot region; hence these changes can be used to modify the transmission spectrum. This can be done
by changing the refractive index of the surrounding medium, by fine tuning the waveguide geometry, and by creating specific structures, such as cavities, to further engineer the band gap.

### 2.1.2.1 Change of the Surrounding Medium

Changing the refractive index of the medium surrounding the slot waveguide changes the effective refractive index \( n_{\text{eff}} \) of the waveguide which has a direct impact on the transmission spectrum. The surrounding medium can be used as an added variable in fine-tuning the properties of the waveguide to allow device reconfiguration though microfluidic control [8].

### 2.1.2.2 Dimensions of the Waveguide

The physical dimensions and the materials of the adjacent slabs and the slot have a strong impact on the slot waveguide mode profile of the slot waveguide, and can be used to engineer the propagation of light through the waveguide. Introducing periodic recesses in the slot opens up a transmission band gap. The dimensions of the silicon slabs and the recesses have a strong impact on the transmission spectrum and can be used to alter the band gap size and position in the wavelength spectrum. The resulting structure, a Bragg slot waveguide with a cavity (BSWC), is discussed and experimentally demonstrated in this work.

### 2.2 Applications

Applications of the slot waveguide in the fields of optical biosensors, optofluidic filters, and optical trapping are discussed in the following sections. An essential aspect for these applications is the ability to deliver a fluid to the critical area of the waveguide in a controlled and robust manner. Slot waveguide structures can be easily integrated with microfluidics technology to achieve this goal. The fluid would be introduced through an enclosed channel passing above the waveguide and perpendicular to it (Fig. 2.3); fluid flow rate can be controlled by regulating the injection pressure.
2.2.1 Optical Biosensors

This section provides an overview of optical biosensors with a focus on refractive index sensors. The components of a sensor are discussed and some examples of slot waveguides for sensing applications are given. To date the slot waveguide concept finds most of its use in sensing applications because it allows the analyte to interact directly with the confined light, rather than the evanescent tail of a guided mode in a solid core waveguide.

Photonic biosensors employ light to interact with the sample of interest. They are very promising candidates for lab-on-a-chip analysis systems because of small dimensions of the sensing area, immunity to the electromagnetic interference, and high sensitivity [2, 12]. Photonic biosensors can utilize labels as a means of detecting specific antigens, or chemicals in the sample, or they can be label-free. Labeled sensors mostly depend on fluorescence detection as a result of specific antibody-antigen binding, whereas label-free sensors depend mostly on the interaction of light with the sample. Labeled sensors offer superior detection capabilities down to the level of a single molecule, however, they require a labor-intensive labeling process which may also alter the functionality of the molecule of interest and affect the resulting measurement [2, 19].

To date, slot waveguides have been used in various sensing applications. The slot geometry is very attractive for sensing of fluids [20, 21] and gases [20, 22] because it allows the direct
interaction of the sample to be measured with the highest field intensity part of the guided mode. The change in the chemistry or concentration of the surrounding medium, which acts as a cover for the guiding slot waveguide structure, parallels a change in its refractive index.

Label-free sensing relies on the detection and quantization of the binding-induced refractive index change [19]. In waveguide-based label-free sensors light of a specific wavelength and polarization is coupled into the waveguide structure on a chip. Specific structures on the chip are designed to optimize the light-sample interaction in a desired way with the analyte usually placed directly on top of these structures. The photonic chip acts as a transducer in a biosensor and converts the biomolecular or chemical detection into a physical signal, such as a wavelength shift in the transmission spectrum.

A transducer functions to convert the chemical or biological signal, such as the binding of a protein antigen to a specific antibody, into a physical signal, the magnitude of which can be measured off chip. In photonic biosensors, a transducer constitutes of a semiconductor chip, on which various waveguide structures and other photonics components are fabricated. The geometry of these components is typically optimized for a specific function with an overall goal of minimizing the device size. A refractive-index–based photonic transducer converts a biological binding event into a shift in the optical spectral features, such as a stop band, or a defect mode. The slot waveguide designed and analyzed in this thesis can be used as a transducer for sensing applications.

A transducer alone does not carry the capability to distinguish between various chemical entities within the analyte. The surface of the transducer typically needs to be functionalized with specific antibodies which will bind specific antigens of interest if they are present in the surrounding analyte (Fig. 2.4). In the field of photonic sensors several standard functionalization schemes have become well developed and are being used more extensively to demonstrate the sensory performance. For example, Biotin/Avidin antibody/antigen pair can be used in the functionalization. Results to date present remarkable sensing capabilities: concentrations as small as 255 fM (femto-Molar) have been detected with a slotted photonic crystal structure [23].
The SOI platform is CMOS-compatible and is well-developed for photonic components which can be integrated together on a chip. Microfluidic channels can be used to deliver a fluid to the features of interest on the chip where fluid can perform either a modifying function, or act as the analyte to be analyzed. This makes SOI photonic waveguides very attractive for lab-on-a-chip applications.

### 2.2.1.1 Slot Waveguide Bragg Grating

A number of groups have been actively working on various implementations of the slot waveguides with periodic corrugations, such as the Bragg grating. Mu et al [24] carried out a theoretical investigation of a slot waveguide with Bragg corrugations on the outer edges of the slabs, which is schematically illustrated in Fig. 2.5.

---

**Fig. 2.4** Schematic illustration of a functionalized transducer.

**Fig. 2.5** Schematic diagram of the Slot Waveguide Bragg Grating [24].
The effects of changing certain waveguide dimensions were studied through modeling. Comparisons were made by analyzing the reflection spectra around a wavelength of 1550 nm and studying the confinement factor $\Gamma$ of the waveguide. TM polarization was used as it results lower propagation loss in the proposed structure.

An increase in the refractive index inside the slot region is reported to increase the peak reflectivity, as shown in Fig. 2.6 (a). This trend is as a result of the field becoming more spread out into the slab regions with increasing slot refractive index. The confinement decreases, and increased electric field intensity at the outer slab Bragg grating interface results in the increased grating-induced reflection. Increasing the slot width, on the other hand, results in reduced peak reflection. This is a consequence of a weaker field confinement in the slot region.

Increasing the number of Bragg grating periods in the structure was found to result in an increase in the peak reflection until saturation occurred at a 98% reflection which was reached with 75 periods, as shown in Fig. 2.6 (b). However, increasing the number of periods has a drawback of increasing the waveguide length which in turn would inadvertently give higher propagation loss for the waveguide.

![Fig. 2.6](image)

Fig. 2.6 (a) Reflection spectrum of slot waveguide grating at varying slot refractive index $n_L$. (b) Peak reflection versus period numbers for different guiding-layer materials. Figures adopted from [24].
2.2.1.2 Pinch Waveguide

A pinch waveguide structure has been proposed by Ryckman and Weiss [25] consisting of an SOI slot waveguide where the geometry of the slot is modified by incorporating an array of holes (Fig. 2.7). The holes decrease in diameter forming a cavity. Similarly to the plain slot waveguide, the highest electric field enhancement and confinement is achieved when the slot width is the smallest. Ultra-fine slot widths, however, are difficult to realize in practice and they provide a smaller interaction volume for light with the analyte of interest as a result of confinement in a smaller volume.

Fig. 2.7 Schematic illustration of a pinch waveguide. Figure adopted from [25].

2.2.2 Optofluidic Filters

Photonic waveguides can be used as optical filters. A waveguide designed to have a transmission or reflection band gap can effectively be used to filter out certain wavelengths from the optical signal. The waveguide dimensions and changes in the surrounding medium are the variables which can be used to fine-tune the band gap wavelength span. Several devices have been demonstrated to date such as a nano-Bragg microcavity filter [26]. Fig. 2.8 illustrates the waveguide geometry and the fluidic tuning capability. This waveguide was integrated with a microfluidic chip for fluid delivery.
Fig. 2.8 Experimental wavelength spectra of the nano-Bragg microcavity filter at different medium refractive indices. SEM micrograph shows the waveguide geometry. Figure adapted form [26].

2.2.3 Optical Trapping

Yang et al [9] demonstrated the capability of an SOI slot waveguide to be used for trapping of the dielectric polystyrene nanoparticles. This is a very promising, albeit relatively novel, area of application for the slot waveguides. The trapping mechanism involves the use of the near-IR forces to confine the matter inside the slot waveguide and scattering/adsorption forces to transport the trapped particles along the slot. Fig. 2.9 illustrates the trapping of the 75-nm polystyrene particles along the slot. A photonic crystal slotted waveguide structure has also been proposed recently for optical manipulation of particles on a nanoscale [10].

Fig. 2.9 Images taken from a movie illustrating nanoparticle capture, transport and release of 75-nm polystyrene nanoparticles along a slot waveguide. Figure adopted from [9].
Chapter 3 Numerical Analysis

Modeling of the slot waveguide can provide an understanding into the device operation and capabilities while avoiding the time-consuming and resource-intensive fabrication and characterization. Different dimensional parameters and material properties can be varied to investigate and optimize the desired structure and to engineer some properties of interest. Once the desired geometry is obtained, the waveguide can be experimentally fabricated and characterized to experimentally demonstrate the desired properties.

Three-dimensional Finite-Difference Time-Domain (3D-FDTD) software from Lumerical Solutions was used to model BSWC waveguide and to investigate the effects of changing its various dimensional parameters. A 3-D model was used to ensure the accuracy of the simulation.

3.1 BSWC Design and Parameters

The slot waveguide with vertical Bragg recesses inside the slot and a cavity formed by elongating one recess is modeled using 3D-FDTD software; this waveguide will further be abbreviated as BSWC (Bragg Slot Waveguide with cavity, Fig. 3.1), whereas the same waveguide without the cavity will be referred to as BSW (Bragg Slot Waveguide).

Fig. 3.1 3-D schematic diagram of BSWC waveguide.
Bragg recesses on the inner slot allow for physical modification of the structure where the guided light intensity is the highest in the slot region and open up a band gap in the transmission spectrum of the waveguide. Periodic recesses on the inner slot side walls have been shown to lead to strong and highly localized electric field enhancements [25] as a result of stronger local effective index modulation on the slot region, when compared to the structure with periodic recesses on the outer side walls of the slot waveguide [24].

Fig. 3.2 illustrates the modeled waveguide with the parameters identified and Table 3.1 lists the values of these parameters. These dimensions for the BSWC waveguide are used throughout this work unless stated otherwise. The silicon waveguide geometry used in this work is based on the nano-Bragg microcavity filter, previously reported by Jugessur et al [26] and applied to the slot waveguide structure. The impacts of changing the dimensions of the waveguide are discussed further in Section 3.4.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slot width</td>
<td>( w_s )</td>
<td>60 nm</td>
</tr>
<tr>
<td>Slab width</td>
<td>( w_{slab} )</td>
<td>220 nm</td>
</tr>
<tr>
<td>Slab height</td>
<td>( h_{slab} )</td>
<td>340 nm</td>
</tr>
<tr>
<td>Recess depth</td>
<td>( d_R )</td>
<td>30 nm</td>
</tr>
<tr>
<td>Recess length</td>
<td>( \ell_R )</td>
<td>200 nm</td>
</tr>
<tr>
<td>Recess period</td>
<td>( P_R )</td>
<td>400 nm</td>
</tr>
<tr>
<td>Cavity recess length</td>
<td>( \ell_C )</td>
<td>400 nm</td>
</tr>
<tr>
<td>Surrounding medium refractive index</td>
<td>( n_{cladding} )</td>
<td>1.000 (air)</td>
</tr>
<tr>
<td>Slab refractive index</td>
<td>( n_{slab} )</td>
<td>3.478 (Si)</td>
</tr>
<tr>
<td>Substrate refractive index</td>
<td>( n_{subst} )</td>
<td>1.444 (SiO₂)</td>
</tr>
</tbody>
</table>

The Lumerical FDTD is a time-dependent Maxwell’s equations solver. Being a time-domain technique, it can be used to solve for a broad range of wavelength values in a single simulation run. The electric field is calculated everywhere within the defined domain as a function of time, which allows to analyze the electromagnetic field movement throughout the model.
Fig. 3.2 BSWC design in 3D-FDTD modeling layout with critical dimensions identified. (a) XY plane view of the waveguide cross-section; (b) Perspective view of the waveguide; (c) XZ view along the waveguide; (d) XZ view with the cavity region magnified.

In order to improve the accuracy of the simulation, a mesh override region is applied to the critical slot waveguide region (i.e. tapers are not included) with a minimum value of 5 nm in the
x-direction, 15 nm in the y-direction, and 12 nm in the z-direction. This mesh override region ensures the high accuracy simulation for the critical structure. Auto non-uniform mesh is used in the remaining simulation region (Fig. 3.3) to reduce the simulation time. A single mode TE-polarized source was used, centered at 1550 nm wavelength. It has been shown elsewhere [20] that the quasi-TE mode exhibits higher confinement factors in the slot region and in the surrounding medium, which results in higher achievable homogeneous sensitivity. Monitors are placed at various locations of the waveguide to record power, transmission spectrum, and other propagation characteristics. Perfectly matched layer (PML) boundary condition is applied to all simulation boundaries, except one: since the structure is perfectly symmetrical in the middle of the waveguide in the z-direction, a non-symmetric boundary condition is applied, which allows to reduce the simulation time by a half.

Fig. 3.3 3D-FDTD simulation diagram identifying mesh override, mode source, monitors, and simulation region.
The elongated recess creates a cavity which allows modifying the transmission spectrum and creating a cavity peak in the middle of the stop band. Fig. 3.4 compares the transmission spectra with varying refractive index of the medium surrounding the slot waveguide. Creating a cavity also results in a wider stop band. Wide stop band on the order of 100 nm in the transmission spectrum allows a high free spectral range, which offers flexibility in tuning the position of the resonant wavelength over a wide range, while the cavity peak allows for a more robust identification of the wavelength shift. Fig. 3.5 illustrates the electric field distribution along the waveguide at the cavity peak wavelength of 1444 nm.

Fig. 3.4 Transmission spectra with varying refractive index of the medium surrounding the slot waveguide for (a) Bragg slot waveguide, and (b) Bragg with waveguide with a cavity.
3.3 Coupler for BSWC

Coupling light into a slot waveguide can be challenging. The light form the broadband source in the characterization setup is carried by a fiber and then can be focused using an objective lens to couple from the free-space into the strip waveguide. The mode profile in the strip waveguide is substantially different than in the slot waveguide because in the former the most of the light is guided in the higher refractive index silicon, while in the latter most of the light is guided in the lower refractive index slot region.

3.3.1 Proof-of-concept Coupler

The BSW device was fabricated and characterized based on proof-of-concept 3D-FDTD modeling results reported previously by our group [27]. The coupler used for coupling light
from the strip waveguide into the slot waveguide is shown in Fig. 3.6. This coupler was used for proof-of-concept demonstration and was not optimized.

![Schematic diagram showing the coupler used to couple light form strip to slot waveguide in BSW samples.](image1)

Fig. 3.6 Schematic diagram showing the coupler used to couple light form strip to slot waveguide in BSW samples.

### 3.3.2 Optimized Coupler

An efficient strip-slot waveguide input and output coupler is an essential component which has to be optimized in order to minimize the insertion losses and back-reflections while optimizing the coupling for an efficient functionality. An efficient strip-to-slot coupler geometry has been recently proposed by Passaro et al [28] and it illustrated in Fig. 3.7.

![Strip-slot coupler geometry.](image2)

Fig. 3.7 Strip-slot coupler geometry. In the insets $E_x$ field distributions at the starting and ending section of the coupler are shown (FEM-calculated). Figure adopted from [28].
This strip-slot coupler geometry is adopted for BSWC waveguide in this work. The value of $h_{\text{min}}$ is reported to be the most important parameter in maximizing the coupling efficiency, which is the highest when the $h_{\text{min}}$ is zero [28]; this is adopted in this work for all the modeling and fabrication designs. In this work we modify this geometry by inverting the tapering section to taper out and away from the slot waveguide. Fig. 3.8 shows the strip-slot coupler used in this work for modeling and fabrication of BSWC waveguide.

Fig. 3.8 Strip-slot coupler geometry for BSWC waveguide. Electric field in the strip and slot waveguide sections is shown.

Fig. 3.9 compares the simulated transmission spectra of the BSWC waveguide with non-optimized coupler illustrated in Fig. 3.6 and the optimized strip-slot coupler illustrated in Fig. 3.8. It is evident that the optimized geometry yields much more efficient coupling, which is reflected in the transmission spectrum shown.
3.4 Numerical Analysis of BSWC

3.4.1 Transmission Spectrum Analysis

The transmission spectrum is widely used to study the performance of a sensor, therefore it is essential to understand how changes in the device geometry will affect the transmission. In the following sections the detailed investigation of the slot width, the slab width, and the length of the cavity recess will be presented.

3.4.1.1 Slot width

The width of the slot in the BSWC waveguide was varied from 40 nm to 70 nm. The resulting transmission spectra are shown in Fig. 3.10. A narrower slot results in a more pronounced stop band and a more evident and narrow cavity peak. This is a direct consequence of the increase of the light confinement in the slot region when the two silicon slabs are brought closer together.
Fig. 3.10 Normalized transmission spectra for BSWC waveguide simulated with varying slot width: (a) 70 nm, (b) 60 nm, (c) 50 nm, and (d) 40 nm slot width.

A similar trend in reduced intensity has been reported by Mu et al [24] where an SOI slot waveguide with Bragg corrugations on the outer sidewalls of the silicon slabs was modeled: the peak reflection was found to decrease as the slot width increased (Fig. 3.11).
3.4.1.2 Slab Width

The width of the two slab regions does not have a significant impact on the device performance in terms of the transmitted optical power and optical intensity [1]. The results of the 3D-FDTD simulations done in this work for BSWC waveguide show that changing the slab width has a stronger impact on the position of the stop band (Fig. 3.12). The confinement factor in the surrounding medium reduces as the slab width increases [20], which can be expected to lead to lower sensitivity. However, for the slot region, the confinement factor was shown to exhibit a maximum for slab widths of 220-240 nm, the exact value being dependent on the surrounding medium [20]. Thus, 220 nm slab width is chosen for the fabrication of the BSW and BSWC devices.
3.4.1.3 Cavity Length

Increasing the length of the resonant cavity recess was found to shift the position of the cavity peak within the stop band to the higher wavelengths (Fig. 3.13). The cavity length of 400 nm was found result in the peak position in the center of the stop band, and was used in the fabrication of the waveguide. A similar trend was reported by Prabhathan et al [12] for a strip waveguide with Bragg corrugations and a cavity (Fig. 3.14)
3.4.2 Sensitivity

The homogeneous sensitivity of the waveguide, defined as [15]:

$$ S_h = \frac{\partial n_{\text{eff}}}{\partial n_{\text{cladding}}} $$

was calculated by modeling the BSWC waveguide with varying refractive index of the surrounding medium $n_{\text{cladding}}$ and analyzing the resulting change in the $n_{\text{eff}}$. Fig. 3.15(a) shows the results. The sensitivity $S_h$ (the slope of this graph) was calculated to be 0.772; in
comparison, Dell’Olio et al [20] reported a homogeneous sensitivity value of 1.0076. The refractive index sensitivity $S_{RI}$ was calculated from Fig. 3.15(b) to be 376 nm/RIU.

![Graphs showing changes in $n_{eff}$ and cavity peak with varying $n_{cladding}$](image)

Fig. 3.15 (a) Change in the $n_{eff}$ of the BSWC waveguide with varying $n_{cladding}$ (b) Shift in the BSWC cavity peak as a function of increasing $n_{cladding}$.

### 3.4.3 Propagation Loss

The propagation loss for the BSWC waveguide with two taper sections was calculated to be 12.78 dB. The lowest optical propagation loss is reported to be 1.7 dB/cm for an asymmetric slot waveguide on an SOI platform with PMMA cladding [29], while the lowest loss with air cladding for symmetric SOI slot waveguides to date has been reported to be 8.6 dB/cm [21].

### 3.5 Summary

BSWC structure was proposed in this chapter and the physical dimensions were identified. 3D-FDTD software from Lumerical was used to investigate the impacts of changing of the slot width, the slab width, the length of the cavity recess, and the refractive index of the surrounding medium on the wavelength transmission spectrum. Reducing the waveguide slot width was found to shift the cavity peak in the transmission spectrum to higher wavelengths and to result in a more pronounced stop band and a narrower peak width. Increasing the silicon slab width was found to shift the stop band with the cavity peak to higher wavelengths. Varying the length of
the cavity recess was found to shift the cavity peak position within the stop band; a doubling of the recess length from 200 nm to 400 nm was found to lead to a symmetrically positioned cavity peak within the stop band. The homogeneous sensitivity was calculated to be 0.722, and the refractive index sensitivity was calculated to be 376 nm/RIU.
Chapter 4 Fabrication

4.1 Overview

The Bragg slot waveguide was fabricated on an SOI platform using the standard microfabrication steps available in a Class 100 (ISO class 5) cleanroom environment. The waveguide pattern was drawn using L-edit software (Tanner Tools) and fractured using the CATSTM software (Synopsys). The pattern was exposed using Electron Beam Lithography (Vistec EBPG5000+) on an SOI wafer (Soitec) coated with ZEP-520A (Zeon Chemicals) positive e-beam resist. The following sections describe the fabrication process in detail. Section 4.2 describes the measures taken to improve the pattern quality. The fabrication process described in the following sections was applied for all samples unless stated otherwise.

4.2 Electron Beam Lithography

An SOI wafer with a 340 nm top layer of silicon and a 1000 nm buried SiO₂ layer was cleaned by immersing in 1% HF for 30 seconds to remove the native oxide layer. The wafer was then cleaned using ultrasonic agitation consecutively in acetone, isopropanol, and DI water for 5 minutes in each. The wafer was blow-dried with a stream of nitrogen gas and further dried on a hot plate at 100°C for 3 minutes. The wafer was allowed to cool down and was spin-coated at 6000 rpm with 400 nm of ZEP-520A positive e-beam resist. The sample was baked on a hot plate at 180°C for 3 minutes. The uniformity of the coating was verified using the Thin Film Thickness Measurement System (Mission Peak Optics). The pattern was exposed onto the sample using Vistec EBPG5000+ Electron Beam Lithography System. Exposure parameters are listed in Table 4.1. Voltage of 100kV was used to ensure high resolution exposure [30]; a small beam current of 0.25 nA and the highest resolution of 2.5 nm available on the Vistec EBPG5000+ tool was used to minimize the beam size and maximize the pattern resolution for the exposure of the most critical features – the slot waveguide and the taper region, while 5 nA at 5 nm resolution was used to expose the less-critical plain waveguide sections, and 30 nA at 50 nm resolution was used for non-essential features such as windows and markers. The higher beam current and lower resolution of the latter was used to maximize the beam spot size and
minimize the beam write time. It should be noted that the resolution and the beam stem size were equal, as a result of the fracturing. The dose test was performed first, scanning the doses of 200 – 290 µC/cm² in a 3x3 exposure matrix to determine the optimum dose for the pattern. Table 4.1 lists the EBL parameters used.

Table 4.1 EBL exposure parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Slot waveguide and taper</th>
<th>Plain waveguide extension</th>
<th>Other features (markers, windows)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>100 kV</td>
<td>100 kV</td>
<td>100 kV</td>
</tr>
<tr>
<td>Beam current</td>
<td>0.25 nA</td>
<td>5 nA</td>
<td>30 nA</td>
</tr>
<tr>
<td>Beam step size/resolution</td>
<td>2.5 nm</td>
<td>10 nm</td>
<td>50 nm</td>
</tr>
<tr>
<td>Dose</td>
<td>250 µC/cm²</td>
<td>250 µC/cm²</td>
<td>250 µC/cm²</td>
</tr>
</tbody>
</table>

The sample was developed in ZED-N50 developer solution and rinsed with a mixture of isopropanol (IPA) and methyl isobutyl ketone (MIBK). The developing solution was kept in a cold bath at -5°C to increase the resulting pattern contrast and to reduce the feature roughness [31, 32]. Lowering of the developer temperature affects the dissolution rates for short and fully-exposed resist segments versus longer and partially exposed ones, which results in faster removal of the fully exposed regions while keeping those partially exposed as a result of proximity effects intact. The sample was hard-baked at 95°C for 1.5 hours. Baking the resist after development is reported to increase the etch resistance and improve the line-edge roughness [33, 34]. Hard-bake at 125°C for 30 min has been reported elsewhere [33] for wet etching. The current fabrication process for the slot waveguide was designed for dry etching, hence a more gentle hard-bake temperature below the glass transition temperature (105°C [35]) was applied to improve the etch resistance. Table 4.2 lists the post exposure development process parameters.

Table 4.2 Post exposure development process parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Medium</th>
<th>Temperature</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Development</td>
<td>ZED-N50 (Zeon Chemicals)</td>
<td>-5°C</td>
<td>60 seconds</td>
</tr>
<tr>
<td>Rinse</td>
<td>MIBK:IPA (9:1 by volume)</td>
<td>22°C</td>
<td>30 seconds</td>
</tr>
<tr>
<td>Dry</td>
<td>N₂ gas stream</td>
<td>ambient</td>
<td>40 seconds</td>
</tr>
<tr>
<td>Hard-bake</td>
<td>Oven</td>
<td>95°C</td>
<td>1.5 hrs.</td>
</tr>
</tbody>
</table>
4.3 Reactive Ion Etching

The samples were etched using the Reactive Ion Etching. BSW samples were etched using the Alcatel 601E RIE tool at the Western Nanofabrication Facility (WNF) at the University of Western Ontario, CA using a modified Bosch process; while BSWC samples were etched using the SPTS ICP RIE System at the James Watt Nanofabrication Centre (JWNC) at the University of Glasgow, UK using the parameters listed in Table 4.3. The remaining resist was removed by placing the samples in ZD-MAC remover (Zeon Chemicals) solution overnight. The samples were subsequently rinsed in acetone, isopropanol, and DI water and blow-dried with a stream of nitrogen gas.

Table 4.3 Etching parameters using to fabricate the device.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SF₆ flow rate</td>
<td>30 sccm</td>
</tr>
<tr>
<td>C₄F₈ flow rate</td>
<td>90 sccm</td>
</tr>
<tr>
<td>Coil power</td>
<td>600 W</td>
</tr>
<tr>
<td>Platen power</td>
<td>12 W</td>
</tr>
<tr>
<td>Pressure</td>
<td>10 mT (3mT/min)</td>
</tr>
</tbody>
</table>

4.4 SEM Inspection

The samples were inspected using a Hitachi S-5200 SEM. Slot width, cavity length, and slab width were inspected and measured for all samples (Fig. 4.1). The results are presented in the following sections.

![Schematic diagram of the Bragg slot waveguide with cavity with the varied parameters indicated.](image-url)
4.4.1 Slot Width

Fig. 4.2 shows SEM micrographs of the BSWC for four different slot widths that were fabricated and characterized. Fig. 4.3 illustrates the discrepancy between the designed and fabricated slot width values. The fabricated widths are on the order of 10% higher than designed. During the etching step the pattern is etched not only vertically but horizontally as well, which results in widening of the slot. The standard deviation is smaller for wider slot. When the slot is very narrow, the proximity effects during the electron beam exposure cause the recess shape distortion and partial joining of the opposing recesses across the slot; this can be observed on some samples where the slot width is the narrowest (Fig. 4.4). It should be noted that a proximity correction can be done in the future to improve the pattern quality for the narrow slot waveguide structures using the GenISys BEAMER software, which was not available for the present work.

Fig. 4.2 SEM micrographs for different slot widths: (a) 43.3 nm slot, (b) 56.2 nm slot, (c) 68.5 nm slot, (d) 79.0 nm slot. (Images taken after etching and resist removal)
Fig. 4.3 Summary of designed and fabricated slot width values. (Measurements made after etching and resist removal)

Fig. 4.4 SEM micrograph showing recess distortion and partial joining of the opposing recesses across the slot. (Image taken after etching and resist removal)

The cross-section of the waveguides was also inspected. Fig. 4.5 shows SEM micrographs for BSW and BSWC devices. Both etching systems, the Alcatel 601E and the SPTS ICP RIE lead the vertical side wall profile. The undulated sidewalls observed for the BSW samples are a result
of the multiple cycling steps used in the modified Bosch process. The BSWC samples etched using the SPTS ICP RIE do not exhibit this side wall pattern.

Fig. 4.5 SEM micrographs showing the BSW cross section (a) *, and BSWC (b).

* BSW waveguide was inspected at the University of Western Ontario. The sample contains resist residue after etching and is coated with 10 nm of Osmium for better imaging quality.

4.4.2 Slab Width

It should be noted that the designed slab width for BSW samples was increased by 40 nm from 220 nm to 260 nm to account for width loss as a result of etching and the WNF facility at the University of Western Ontario. After etching, SEM inspection revealed that 40 nm offset was not sufficient, as the resulting slab width was 217 nm (standard deviation is 5.1 nm). Thus, for BSWC samples the slab width offset was increased to 45 nm to the designed slab width of 265 nm. However, SEM inspection after etching at the JWNC facility at the University of Glasgow revealed zero slab width reduction as a result of etching. Hence, all BSWC samples have the fabricated slab width of 265 nm (standard deviation is 2.6 nm), unless stated otherwise.

4.4.3 Cavity Length

The length of the cavity affects the spectral peak position within the stop band. The cavity length was measured by taking an average of 20 measurements, 10 of which were made at the
narrowest region of the slot waveguide, and the other 10 were taken at the widest region (Fig. 4.6). The high standard deviation of the cavity length values is a result of the low recess angle; Fig. 4.7 summarizes the measurements.

Fig. 4.6 SEM micrograph showing recesses in the Bragg slot waveguide, illustrating how the recess length was measured. (Image taken after etching and resist removal)

Fig. 4.7 Summary of designed and fabricated cavity length values. Numbers above each blue column pair indicate the designed cavity length value. (Measurements made after etching and resist removal)
4.5 Pattern Quality Improvements

The impact of the resist thickness and the development temperature were investigated to improve the feature sharpness and reduce the edge roughness [31, 32, 36]. The lower development temperature changes the dissolution rates for shorter and longer molecular segments in the resist. This allows for shorter and fully exposed segments to dissolve faster than longer and slightly-exposed segments, leading to higher contrast and increased pattern quality [32]. The effects of resist thickness and development temperature were evaluated by comparing against three parameters: slab width, recess angle, and recess length (Fig. 4.8).

The results are presented in the following sections. It was found that the resist thickness does not have a strong impact on the pattern quality, however thicker resist is better for the etching step. Hence, a 320 nm resist thickness was chosen. It was found that lower development temperature results in higher pattern quality and higher dimensional correspondence between designed and fabricated values, hence the development temperature of -5°C was chosen.

![Schematic illustration of the Bragg slot waveguide; the parameters used to assess the pattern quality are labeled.](image)

To obtain a thinner resist coating ZEP-520A resist was diluted 1:1 by volume with anisole to result in 150 nm resist thickness; after the exposure, development, and hard-bake the resist thickness decreased to 120 nm. Non-diluted ZEP-520A resist was spin coated to give 400 nm thick resist layer, which after exposure, development and hard-bake decreased to 320 nm. Four samples were prepared in total: two with 120 nm resist and developed at 22°C and -5°C, and another two with 320 nm resist and developed at 22°C and -5°C. Table 4.4 summarizes the resulting resist thickness values.
Table 4.4 Summary of two resist concentrations used and the resulting differences in pattern quality parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Resist diluted 1:1</th>
<th>Non-diluted resist</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resist thickness* before exposure</td>
<td>150 nm</td>
<td>400 nm</td>
</tr>
<tr>
<td>Resist thickness* after development and hard-bake</td>
<td>120 nm</td>
<td>320 nm</td>
</tr>
</tbody>
</table>

* The resist thickness was measured using the Thin Film Thickness Measurement system MP100-S (Mission peak Optics). The measurement precision is 0.1 nm.

4.5.1 Slab Width

The slab width has a strong impact on the stop band and the cavity peak position in the spectrum. The width of the Si slab is very sensitive to over-exposure during the lithography step, the under and over-development, and etching, all of which can contribute to the slab being narrower, or wider, than the designed value.

The slab width measurements were obtained from SEM micrographs. The average values and standard deviations were calculated over 10 measurements for each sample. Fig. 4.9 summarizes the results. The standard deviation of 3.4 nm is the smallest for the sample with 320 nm thick resist and developed at -5°C, and the slab width value of 235.7 nm is found to be the closest to the designed value of 260 nm. It should be noted that the desired slab width taken from modeling results is 220 nm, but the designed width was increased to 265 nm to account for decrease in the dimensions after etching.

![Slab width at different resist thickness and development temperatures. (Samples are analyzed after development and hard-bake)](image-url)
4.5.2 Recess Angle

The designed recess angle was 90°. However, due to the small recess width of 30 nm and the increasing exposure proximity effects at this scale, the recess angle is expected to be reduced significantly. Fig. 4.10 shows an SEM micrograph of a typical sample. The line at the recess illustrates how the recess angle was measured. The average values and standard deviation were calculated over 10 measurements for each sample. Fig. 4.11 summarizes the results. The standard deviation values are comparable for all samples. The sample with thicker resist and developed at -5°C has the recess angle value of 34.1°, which is the closest to the designed value of 90°.

Fig. 4.10 SEM micrograph showing recesses in the Bragg slot waveguide, illustrating how the recess angle was measured. (Image taken after development and hard-bake)

![SEM micrograph](image)

Fig. 4.11 Recess angle at different resist thickness and development temperatures.
4.5.3 Recess Length

The designed recess length taken from the modeling results is 200 nm. This parameter is strongly influenced by the recess angle, as shown previously in (Fig. 4.7) in Section 4.4.3. Very low recess angle results in very large difference in these two points of measure, which gives a high standard deviation. Fig. 4.12 summarizes the results. The sample with 320 nm resist thickness and -5°C development temperature was found to have the smallest standard deviation of 28.9 nm and the average recess length of 190 nm, which is the closest to the designed value of 200 nm.

![Fig. 4.12 Recess length at different resist thickness and development temperatures.](image)

4.6 Summary

Electron Beam lithography and reactive ion etching were used to fabricate the Bragg slot waveguide with the cavity. Scanning electron microscopy was used to image the fabricated samples are to evaluate the pattern quality based on the slot width, the slab width, and the cavity recess length. The resist thickness and the development temperature were varied to improve the pattern quality. The resist thickness of 320 nm and the development temperature of -5°C were used to fabricate the BSWC samples for the characterization.
Chapter 5 Characterization

In this chapter the characterization of the samples fabricated using the ELB will be discussed. The characterization setup used for the experiments will be presented followed by the analysis of the transmission spectra and evaluation of the waveguide performance.

5.1 Overview of the Characterization Setup

The experimental setup used to characterize the BSW and BSWC is shown in Figure 5.1. End-fire coupling was used to couple the light into and out of the waveguide. A broadband SLD source (ThorLabs S5FC1005S) centered at 1550 nm wavelength was used in combination with a C-band EDFA booster amplifier (JDS Uniphase OAB1552) as the source for characterization. The light was coupled from a single mode fiber into the free space using a collimator. A TE polarization was achieved using a half-wave (λ/2) plate and a polarizing beam cube (PBC). The sample was mounted on a Luminos stage with 3-dimensional position control, and held in place using the vacuum suction. Two objective lenses (40×) were used to couple light in and out of the sample. A flip-mirror was used to guide light from the sample into either an IR camera, or a collimator to couple light from free space into the single mode fiber. The fiber was connected to a power meter when optimizing the output power, or to the OSA (ANDO AQ6317B) when recording the transmission spectrum.

Fig. 5.1 Schematic diagram of the experimental setup used to characterize the waveguides.
The coupling of light in and out of the waveguide was first optimized using the IR camera and the power meter. Once the maximum transmitted power was achieved, the transmission spectrum was recorded. The background transmission spectrum was recorded using the setup exactly as described, but without the sample. All transmission spectra used in the following sections represent the transmission taken with the sample minus the background transmission.

5.2 Analysis of the Geometrical Parameters

Two sets of nine BSWC samples were fabricated for characterization, each containing four sets of waveguides with varying width of the slot. Each sample was designed with a slightly different physical dimension in order to characterize a range of parameters. The slot width, slab width, and cavity length were varied to experimentally investigate the effects of changing these variables on the light coupling in the waveguide and the resulting transmission spectrum and to compare the results against the FDTD modeling. With decreasing device dimensions the sidewall and surface roughness as well as ultra-fine particle contamination from the surrounding air are expected to play a more significant role as device dimensions become more comparable to the dimensions of these defects. This is expected to lead to the differences in the experimentally obtained spectra compared to modeling.

5.2.1 Slot Width

The transmission spectra taken for the waveguides with varying slot widths show decreasing stop band intensity and a shift to lower wavelengths as the slot width increases. As the slot width increases and the two slabs forming the slot waveguide eigenmode become more distanced from one another; the intensity of the guided light in the slot decreases, as the coupling of the slab eigenmodes becomes less efficient. This results in a less pronounced stop band in the spectrum. These results agree with the 3D-FDTD modeling as well as some previous work on the slot waveguides by other authors [1, 24]. Fig. 5.2 shows the transmission spectra for BSWC waveguides and compares it to the 3D-FDTD simulated transmission. Despite the small increase in the slot width as a result of etching, the peak positions are in a good agreement.
5.2.2 Slab width

The silicon slab width was varied for BSWC geometry. Fig. 5.3 shows the resulting spectra. A clear shift in the cavity peak and the stop band to longer wavelength with increasing of the slab width is observed. This is in a fair agreement with 3D-FDTD modeling results for the same slab width variation. Fig 5.4 shows the shift in the cavity peak position as a function of the increasing slab width for both the simulated and the experimental spectra. The peak positions in the experimental spectra are shifted to the lower wavelength values, which can be attributed to the waveguide sensitivity to the fabrication-related dimensional imperfections [26]. The trend for the peak shift with the slab width, however, is in a good agreement with simulation results,
showing a discrepancy of 0.83% as calculated from the slopes of the linear trend line fits for each graph.

Fig. 5.3 Transmission spectrum of BSWC samples at varying silicon slab width: (a) 250 nm, (b) 265 nm, (c) 290 nm, (d) 315 nm. Peak positions for each spectrum are indicated with arrows of corresponding color.
5.2.3 Cavity Length

The length of the recess forming the cavity in the BSWC was varied also, and the experimental spectra are shown in Fig. 5.5. As expected based on modeling results, increasing the length of the cavity recess shifts the position of the cavity peak within the stop band to higher wavelengths. The Trend is in the agreement with the simulation results. Fig 5.6 shows the cavity peak position from the transmission spectrum as a function of the cavity recess length. The experimental peak positions are shifted to the higher wavelength values by approximately 20 nm; this is attributed to fabrication imperfections such as the slot side-wall roughness and individual recess distortions. The trend for peak shift with cavity recess length, however, is in a good agreement with simulation results with a discrepancy of 0.96% as calculated from the slopes of the linear trend line fits for each graph.
Fig. 5.5 Experimental transmission spectra for waveguides with different cavity lengths taken in air: (a) cavity length 350 nm, (b) cavity length 410 nm, (c) cavity length 450 nm, (d) cavity length 500 nm. A vertical dashed line shows the approximate position for the left band edge at 1523 nm for all spectra. A solid bold line in each spectrum is a hand-drawn visual aid. The arrow on each spectrum indicates the cavity peak position.
The effect of the recess shape was studied through the modeling of the BSWC waveguide with the recess shape adjusted from the experimental SEM imaging results, where the recess angle was found to be approximately 35° instead of the designed 90°. Fig. 5.7 compares the shift in the cavity peak position as $n_{cladding}$ is increased from 1.000 (air) to 1.333 (water) for waveguide with 35° and 90° recess angles.

Fig. 5.7 Shift in the cavity peak position as a function of increasing $n_{cladding}$ for BSWC waveguide with 35° and 90° recess angles. (Trend lines are a linear fit).
A very small shift in the peak position to lower wavelength is observed on decreasing of the recess angle to 35°, which reflects in the slight reduction in the sensitivity of less than 0.9% from 368.47nm/RIU to 365.17 nm/RIU. Thus, this significant change in the recess angle and in the recess shape as a result of the fabrication process limitations does not have a strong impact on the wavelength spectrum and on the resulting waveguide performance.

### 5.3 Characterizing Performance

The sensitivity performance of the BSW and BSWC waveguides were characterized by placing fluids with different refractive indices on the device surface. Water ($n_{\text{water}} = 1.333$), isopropanol (IPA, $n_{\text{IPA}} = 1.3776$), and refractive index 1.3100 liquid (Cargille Laboratories, $n_{1.31} = 1.3100$) which will be further abbreviated as RI1.31, were used for characterization. A drop of fluid was placed on the aligned sample using a cleanroom pipet, such that it covers the whole device surface. It was not possible to use a smaller fluid droplet because of very fast evaporation of water and isopropanol at such small volumes. After recording the transmission spectrum the droplet was removed by absorbing it using a cleanroom-compatible cotton swab. A transmission spectrum taken immediately after removing the droplet was found to be in a good agreement with the original spectrum taken in air; this implies that absorbing the droplet with a cotton swab is sufficient to remove all the liquid from the sample. Fig. 5.8 demonstrates the results. It should be noted that this method was not used for RI1.31 fluid due to its higher viscosity. Moreover, piranha cleaning can be done between testing of different fluids to further ensure the accuracy of the measurement, especially when using the fluids with varying physical properties. Trace amounts of material remaining on the waveguide surface or trapped within the slot waveguide can have a strong influence of the experimental spectrum by influencing the surface sensitivity [14] of the waveguide. Trace amounts of contaminants become especially critical when characterizing using the changes in the concentration of glucose in water for example, where glucose molecules adsorbed onto the surface or trapped within the slot due to surface tension effects can influence the subsequent measurement of a different concentration.
5.3.1 RI Sensitivity

Fig. 5.8 BSW transmission spectra taken in air before placing a water droplet on the device surface, and immediately after removing the droplet with a cotton swab. The curve for the transmission after water removal may not be visible as it overlaps with the curve for the transmission taken in air.

Fig. 5.9 BSWC transmission spectra taken using air, water, IPA, and RI1.31. Cavity peaks for IPA and RI1.31 fall outside of the detectable wavelength range, which is limited by the wavelength span of the broadband source. However, the left edge of the stop band can also be used to estimate the sensitivity.

Fig. 5.9 BSWC transmission spectra taken using air, water, IPA, and RI1.31 as $n_{\text{cladding}}$. Sample specifications: slot width 43.3 nm, slab width 250 nm, cavity recess length 400 nm.
For all the samples which were characterized the stop band of RI1.31 was shifted towards a higher wavelength than for water and IPA, which both have a higher refractive index and are predicted through the modeling to have a smaller wavelength shift than RI1.31. A possible reason for this inconsistency may lie in the different chemistry of the fluids used in characterization and their corresponding behavior on a nanostructured surface. RI1.31 fluid is made of perfluorocarbons and chlorofluorocarbons and has a significantly higher viscosity and a lower surface tension when compared to isopropanol and water (Table 5.1). Based on this, RI1.31 can be expected to behave differently when placed on the slot waveguide surface. Whereas water and IPA may not penetrate into the slot region due to the higher surface tension, RI1.31 might. This can explain the higher stop band shift for this fluid and the resulting higher sensitivity of 445 nm/RIU compared to 319 nm/RIU based on the air-water-IPA trend, as depicted in Fig. 5.10. These results suggest that the waveguide is sensitive to the surface tension of the cover fluid besides its refractive index. However, in biosensing applications typically a single medium such as waver is used, in which various entities of interest are dissolved.

Table 5.1 Viscosity and surface tension for RI1.31 fluid, water, and IPA.

<table>
<thead>
<tr>
<th></th>
<th>RI1.31*</th>
<th>Water **</th>
<th>IPA**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viscosity</td>
<td>14 mPa·s</td>
<td>1.0 mPa·s</td>
<td>2.1 mPa·s</td>
</tr>
<tr>
<td>Surface tension</td>
<td>18 dynes/cm</td>
<td>71.97 dynes/cm [16]</td>
<td>21.70 dynes/cm [16]</td>
</tr>
</tbody>
</table>

*Viscosity and surface tension valued are taken from Supplier Cargille Laboratories MSDS for Series AAA 1.3100 RI fluid.

**Viscosity of water and IPA were obtained from Dow Corning MSDS.
The sensitivity based on the modeling was calculated to be 376 nm/RIU, and lies in between the experimental 319 nm/RIU and 445 nm/RIU. With respect to water and IPA as RI shift characterization fluids, it further supports the idea that these fluids do not fully penetrate into the slot, which results in the lower sensitivity. For RI1.31 fluid, however, the experimental sensitivity is higher than the theoretical value. A possible cause for this may lie in the surface adsorption of the perfluorocarbons and chlorofluorocarbons from the RI1.31 fluid into the waveguide or the substrate surface, leading to increased surface sensitivity; this can be studied in a greater detail in the future.

5.3.2 Detection Limit

The ability to accurately measure the spectral shift from the sample can be expressed as the detection limit ($DL$) for the waveguide [14]:

$$DL = \frac{R}{S}$$  \hspace{1cm} (9)
In refractive index sensing this value represents the smallest detectable refractive index change of the medium which can be detected using the particular waveguide device. $DL$ depends on the sensor sensitivity $S$ in nm/RIU and the sensor resolution $R$ in nm, which represents the smallest refractive index change which it is possible to measure using a given equipment. $R$ can be limited by the resolution of the source or the resolution of the detector used in the experimental setup. In this setup the resolution-limiting factor is the OSA resolution, which for the instrument used is 0.01 nm (ANDO AQ6317B OSA). Thus, the experimental detection limit is calculated to be $3.13\times10^{-5}$ RIU for air-water-IPA sensitivity, and $2.25\times10^{-5}$ RIU for air-R11.31 sensitivity. These values are comparable to previously reported detection limits for similar structures [12, 13, 22].

5.3.3 FSR Analysis

Peaks of various width and intensity were found to overlay the transmission spectrum; they arise as a result of propagation and reflection losses from various points along the waveguide. The free spectral range formula can be used to determine the waveguide dimensions which give rise to certain spectral features:

$$\Delta \lambda = \frac{\lambda_0^2}{2n_{eff}\ell}$$  \hspace{1cm} (10)

where $\Delta \lambda$ is the wavelength between the two successive transmitted optical maxima or minima; $\lambda_0$ if the wavelength at which these maxima or minima are observed; $n_{eff}$ is the effective refractive index of the medium in which light travels; $\ell$ is the length of the waveguide feature giving rise to the spectral features of interest. Examples of typical transmission spectra are shown in Fig 5.11 with $\Delta \lambda$ and $\lambda_0$ for some features of interest identified.

Table 5.2 summarizes the variables and the calculated $\ell$. The calculated value of 44.502 µm can be attributed to reflections form the facets of the tapered sections; the value of 99.397 µm – to the reflections from the whole waveguide minus the 2 µm strip waveguide sections (Fig. 5.12). These reflections make the coupler and the taper less efficient and lead to high strip-to-slot coupling losses. The taper and the coupler geometries can be optimized to ensure the slow and gradual geometrical and effective index variation along the waveguide.
Fig. 5.11 BSWC transmission spectra identifying features of interest (1), (2), and (3). (a) BSWC with slab width 265 nm, (b) BSWC with slab width 290 nm.

Table 5.2 Variables and their values used in the FSR calculations.

<table>
<thead>
<tr>
<th>Variable</th>
<th>(a)</th>
<th>(b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_0$</td>
<td>1507 nm</td>
<td>1536 nm</td>
</tr>
<tr>
<td>$\Delta\lambda$</td>
<td>8.6 nm</td>
<td>4.0 nm</td>
</tr>
<tr>
<td>$n_{eff}$</td>
<td>2.967</td>
<td>2.967</td>
</tr>
<tr>
<td>$\ell$</td>
<td>44,502 $\mu$m</td>
<td>99,397 $\mu$m</td>
</tr>
</tbody>
</table>

Fig. 5.12 Schematic diagram of the BSWC waveguide showing the critical dimensions giving rise to the FSR spectral features.
5.3.4 Propagation Loss

A transmission spectrum (Fig. 5.13) taken at 0.05 nm OSA resolution was used to calculate the propagation loss for the 4 mm long BSWC waveguide on chip. The effective index of 3.09 in the 2 µm wide section of the strip waveguide was used in the calculation. The propagation loss was calculated to be 22.0 dB/cm, or 8.8 dB per 4mm long sample with the waveguide. The lowest propagation loss for symmetric SOI slot waveguides to date has been reported to be 8.6 dB/cm [21].

![BSWC waveguide transmission spectrum](image)

Fig. 5.13 BSWC waveguide transmission spectrum taken at 0.05 nm OSA resolution.

The silicon thickness used in this work was 340 nm, while many other studies on similar structures typically use lower thickness core [13, 20, 21, 37]. Waveguide grating with a higher thickness has a higher loss due to the out-of-place scattering during reflection [12]. This loss can be reduced by reducing the thickness of the silicon guiding layer. However, this would in turn broaden the cavity peak width, which is not desirable for wavelength shift detection applications. Another avenue to explore in minimizing the loss is the duty cycle. Prabhathan et al [12] reported that increasing the duty cycle can reduce loss (Fig. 5.14). Moreover, propagation losses on the order of 2 dB/cm have been demonstrated in asymmetric slot waveguides [30, 37, 38], an approach which is certainly applicable to the Bragg slot waveguide geometry presented in the current work. An increase in the duty cycle results in smaller air gaps in the narrower regions of the grating. This increases the effective index of the grating period resulting in
improved mode mismatch between the alternating regions of the grating and helps to minimize the propagation loss.

![Graph showing 3dB band width and loss variation](image)

Fig. 5.134 Variation in 3dB band width and loss inside the cavity with respect to grating duty cycle [12].

### 5.4 Summary

The fabricated samples were characterized using the end-fire coupling approach. The transmission spectra were analyzed and the waveguide performance was assessed. The trends in varying the dimensions of the slot width, the slab with, and the cavity recess length were found to be in agreement with the modeling results, demonstrating the versatility of using the numerical analysis to study Bragg slot waveguide structures. The refractive index sensitivity was calculated to be 319 nm/RIU for the air-water-IPA measurement, and 445 nm/RIU for the air-RI1.31 measurement. The difference in the sensitivity values was attributed to different physical properties of the characterized fluids; the low surface tension and high viscosity of the RI1.31 fluid is suggested to result in a greater penetration of the slot region by the fluid resulting in an increased light-matter interaction. The free spectral range analysis of the features in the transmission spectrum was done and a correlation with the various facets within the waveguide structure was found. The propagation loss in the fabricated waveguide of 4 mm length was calculated to be 8.8 dB.
Chapter 6 Future Work

6.1 Optical trapping

Optical trapping is a very novel and promising application field for the slot waveguides. Work by other authors [9, 10, 39-41] continuously demonstrates the potential of slot waveguides for optical trapping. Exploring this application area was outside of the scope of the current work due to lack of time and materials for the experimental setup. However BSWC waveguide would be suitable for such analysis. Theoretical modeling can be done in the future to analyze and optimize the optical trapping force [9, 10, 40, 41], while characterization with optical trapping can be done once the waveguide is integrated with a chip for the controlled flow.

6.2 Improving Performance

Further optimization of the BSWC waveguide to improve the sensitivity and to minimize loss is needed. The design and optimization of an adiabatic taper and a more efficient coupler for the proposed structure is essential in order to improve the waveguide performance and remove the overlaying spectral features discussed in section 5.3.3 which complicate the accurate analysis of the experimental transmission spectra. In addition to the refractive index sensitivity $S_{RI}$ which deals with the bulk changes in the refractive index, the surface sensitivity [14] can be analyzed to evaluate the potential for biomolecule capture and detection of the slot waveguide surface. Geometrical parameters such as recess dimensions and silicon thickness of the waveguide can be modeled and optimized. Furthermore, the waveguide can be combined with other photonic components such as photonic crystals to add another dimension in fine-tuning the waveguide performance. Possible improvements and suggested future work are discussed in the following sections.
6.2.1 Photonic Crystal Slot Waveguide

Increasing the quality factor has a benefit of making the cavity peak in the transmission spectrum narrower. This makes the detection of ultra-fine shifts the peak position much more robust. Photonic crystal waveguides offer higher degree of light manipulation such as directing, splitting, confining, slowing down, and they offer high quality factor cavities [6]. Photonic crystal cavities are generally small, which gives rise to the high free spectral range of the order of 100-200 nm. Cavity peak width can also be reduced and the Q factor increased by coupling of the several cavities in the waveguide [12].

Recent advancements in the photonic crystal waveguides suggest them as a very promising structure for biosensing applications. Combining the unique optical properties of the slot waveguides and photonic crystals leads to refractive index sensitivities on the order of 1700 nm/RIU with a detection limit of on the order of $10^{-6}$ RIU [42]. A recent review by Scullion et al [6] looked at the progress and future directions for these devices. Slotted photonic crystal waveguides have a high sensitivity as a result of the spatial confinement of light and temporal confinement arising from the slow light effects in the void slot where it can interact directly with the analyte [43]. Fig. 6.1 shows the device which was proposed and characterized [6].

A comb slot photonic crystal waveguide has been proposed in 2011 by Caer et al [44]. This geometry is particularly attractive as it allows for a wider slot width of 300 nm, while providing

Fig. 6.1 Slotted Photonic Crystal waveguide with resonant defect couplers. Figure adapted from [6].
the high optical intensity inside the slot as shown in Fig. 6.2. A wider channel is easier to realize in practice and introducing fluids into a wider slot is less dependent on the fluid surface tension and viscosity and will allow for more light-sample interaction.

6.2.2 Etching silicon dioxide cladding

The bottom cladding layer in the slot photonic crystal waveguides is typically etched using HF to result in a suspended structure with air as the bottom cladding [6]. This preserves the critical device structure and helps to enhance the confinement and guiding in the slot by providing a higher refractive index contrast (glass-silicon vs. air-silicon). The same step can be applied to the Bragg slot waveguide geometry. Fig. 6.3 shows the theoretical sensitivity enhancement from 376 nm/RIU to 424 nm/RIU when the substrate is removed.
6.2.3 Optical Damage

Yang et al [9] reported using optical power of less than 300 mW for optical the trapping experiments. In the BSW and BSWC characterization described in this work the optical power of less than 20 mW was used. To our knowledge no lower power optical trapping using the slot waveguides has been reported to date, hence it is likely that a source with optical power above 20 mW would be necessary for optical trapping experiments. Optical damage can be of concern when using a high input power for the characterization. Pattern damage was observed on some BSWC samples inspected using SEM after the characterization as shown on Fig. 6.4. No damage was observed at the sample edges or any other regions of the sample after the optical characterization. The slot waveguide is designed to have an enhanced optical intensity in the slot region which may lead to the slot being more prone to damage. Moreover, the samples were characterized using the different refractive index fluids on top of the sample, which contributes to higher light confinement in the slot and an increased light intensity in the slot. An investigation into the cause of this damage is beyond the scope if this work, but the possibility of this being an optical damage cannot be ruled out.
6.3 Microfluidics integration

For lab-on-a-chip applications the biosensor can be integrated with a microfluidic channel for controlled and efficient sample delivery to the waveguide sensing area. The fluid of interest can then be removed and the device can be rinsed allowing it to be used multiple times. Numerous photonic sensing chips have been integrated with the microfluidics [6, 26, 45]. The fabrication of a microfluidic chip is a well-established process; however it can be challenging to make it sufficiently small to accommodate a very small device, as is in the case of the BSWC waveguide proposed in this work. The sensing slot and tapers combined require a 90 μm × 4 μm area; a microfluidic chip of such dimension is not possible to make using the current state of technology. However, in a truly lab-on-a-chip device numerous sensing waveguides and other components are to be integrated on a single chip for multifunctional and multi-sample capabilities, and the chip size will inevitably become larger and compatible and microfluidics integration would be more feasible.

6.4 Surface Functionalization

The waveguide by itself cannot be used only for concentration sensing of a sample containing only one component. The waveguide by itself is not capable of distinguishing between various molecules which are typically present in a biological or chemical sample. The device surface
inevitably needs to be functionalized in order to allow for a true sensing capability. A common functionalization scheme used in photonic biosensors involves straight-forward surface chemistry to attach an antibody (Biotin) to the device surface, which selectively binds an antigen (Avidin) from a complex sample. A typical process is described by Scullion et al [6] and is schematically illustrated in Fig. 6.5; APTES (aminopropyltriethoxysilane) is used to immobilize Biotin on the silicon surface. Both silicon and silicon dioxide surfaces can be functionalized with this scheme which is especially useful for a slot waveguide device because both silicon slabs and the underlying silicon dioxide cladding can be functionalized to increase the sensing area for a potential antibody-antigen binding. Alternatively, either silicon side wall of the slot or the silicon dioxide bottom of the slot can be selectively functionalized to improve the surface sensitivity and selectivity towards the small molecule interactions.

![Diagram of Biotin functionalization using APTES](image)

**Fig. 6.5 Biotin functionalization of silicon surface using APTES.** (a) Silicon immersed in Piranha solution to expose OH groups on surface; (b) APTES links to OH groups on surface and presents NH2 groups; (c) NHS linked biotin attaches to NH2 groups; (d) Avidin captured by immobilized biotin.
Chapter 7 Conclusions

7.1 Numerical Analysis

In this thesis the 3D-FDTD software (Lumerical) was used to model the BSWC and investigate the impact of changing the geometrical parameters of the waveguide on the performance of the device through the transmission spectrum of the waveguide. Reducing the waveguide slot width was found to shift the cavity peak in the transmission spectrum to higher wavelengths and to result in a more pronounced stop band and a narrower peak width at FWHM. Increasing the silicon slab width was also found to shift the stop band with the cavity peak to longer wavelengths, without altering the overall shape of the transmission spectrum. Varying the length of the cavity recess was found to shift the cavity peak position within the stop band; a doubling of the recess length from 200 nm to 400 nm was found to lead to a symmetrically positioned cavity peak within the stop band.

7.2 Fabrication

In Chapter 4, the developments in the fabrication process for the slot waveguide were discussed in detail. The narrow slot and the periodic recesses in the proposed structure lead to several fabrication challenges, which were addressed in developing the fabrication protocol. In particular, reducing the development temperature to -5°C was found to improve the pattern quality of the waveguide, and was used to fabricate the waveguides for the characterization. Distortions on the Bragg recesses and partial joining of the opposing recesses were observed for waveguides with narrow slot widths on the order of 40 nm. This was attributed to proximity effects during the electron beam lithography exposure. It was found that reducing the resist thickness does not have a favorable impact on the pattern quality, thus a thicker resist coating was used in the fabrication of samples for the characterization. BSW and BSWC samples were etched using different etching tools. BSW samples were etched using the Alcatel 601E RIE tool; the etching quality was found to be more isotropic, leading to 45 nm reduction of the silicon slab width in the etched waveguides. BSWC samples were etched using the SPTS ICP RIE system;
the etching quality was found to be highly anisotropic, leading to virtually zero change in the waveguide dimensions.

7.3 Characterization

The resulting waveguides were characterized using the end-fire coupling approach. The transmission spectrum was used to analyze the waveguide performance. The results were found to be in a good agreement with modeling results. The impacts of varying the dimensions of slot width, slab with and the cavity recess length were found to be in agreement with modeling results, demonstrating the versatility of using numerical analysis to study Bragg slot waveguide structures. The refractive index sensitivity of the fabricated device was found to be dependent on the properties of the fluids used in the characterization. The fluid with lower surface tension and a higher viscosity was found to lead to higher sensitivity, compared to fluids with higher surface tension and lower viscosity; the differences are attributed to the extent of the fluid filling the slot region. The higher is the spatial overlap between the fluid of interest and the electric field confined in the slot regions, the higher is the sensitivity of the waveguide. The free spectral range analysis of the features in the transmission spectrum was done and a correlation with the various facets within the waveguide structure was found.

7.4 Suggested Future Works

Further optimization of the BSWC structure would be essential for realizing its full potential for use in optofluidic, sensing, or optical trapping applications. The silicon slab height and recess dimensions were not analyzed in this work and present another avenue for exploration. The impact of the dimensional parameters on the sensitivity and propagation losses can be studied in a greater detail in order to optimize and improve on the structure. In addition, the BSWC can be combined with other photonic components such as photonic crystals for further fine tuning of the device functionality. This presents a new dimensions and further flexibility to fine-tune the desired properties of the structure. A wet etching step can also be incorporated in the fabrication of the waveguide to remove the silicon dioxide substrate under the slot waveguide structure, which would suspend it in air and lead to higher sensitivity. The waveguide can be integrated with a microfluidic chip for controlled fluid flow and delivery for more robust and accurate
characterization. This would allow the waveguide surface to be functionalized to demonstrate the performance of the structure as a sensor; while the controlled flow would allow to investigate the optical trapping potential of the waveguide.

7.5 Summary

In this thesis a Bragg Slot Waveguide with a Cavity was designed, fabricated and characterized. The analytical and experimental results were shown to be in a good agreement emphasizing the importance and effectiveness of using analytical methods for modeling and optimization of photonic components. The fabrication protocol of the BSWC was developed. The variations between designed and experimental waveguide performance were attributed to the increasing importance of atomic-scale imperfections as the waveguide dimensions approach several tens of nanometers. The propagation loss was measured to be 8.8 dB for the whole device of 4 mm length with the critical component length of 10 µm. Possible improvements in the device performance and the future work were discussed. The presented device is compact, easily tunable, and can be integrated with the microfluidic technology for optofluidic, sensing, and optical trapping applications.
Publications

References


