Graduate School of Advanced Science and Engineering
Waseda University

博 士 論 文 概 要
Doctoral Thesis Synopsis

論 文 題 目
Thesis Theme

Integrated Silicon waveguide biosensors with Bragg gratings and rectangular resonators

申 請 者
(Applicant Name)

Manuel	MENDEZ ASTUDILLO
メンデス アストゥディージョ	マヌエル

Department of Pure and Applied Physics, Research on Photonic Devices

September, 2017

Silicon photonics is revolutionizing many fields that range from biochemical sensors, data communication, nonlinear applications to microwave signal processing. In the past recent years, the research efforts from many groups have significantly increased, and are foreseen to keep growing for the next decade. The reason why there is great interest in silicon photonics is that light, in the C band, can be confined, transmitted, routed and manipulated in structures with dimensions in the nanometer order, thus allowing high integration. The physical reason is the high contrast of the refractive index between the waveguide and the substrate and that silicon is transparent at those wavelengths. A second reason of the popularity of silicon photonics, is that this technology benefits from the already existing fabrication facilities of electronic devices, as most of the photonic processes are CMOS compatible. Therefore, the future and the opportunities that exist in this field are mainly in device engineering and system engineering with one of the biggest markets in biochemical sensors.

Nowadays, biochemical sensors are in great need as new applications emerge such as point-of-care and optical trapping. In the medical context, the reliability of a medical diagnose heavily depends on the correct detection and quantification of specific biomarkers, and in extreme cases, single molecule detection is wanted. Other applications, such as food and water quality control require fast and disposable sensors to detect large concentrations of contaminants. It is here that silicon photonics plays a key role, as devices based on this technology provide a wide range of versatility, as they can detect down to single molecules, perform real time measurements and the fabrication cost is low that they can be disposable. Some devices on silicon have been already demonstrated to have sensitivities superior to other technologies and great efforts have also been made to pack and integrate the device with other components to obtain a sensing platform such as lab on a chip. The main part of such a platform remains in the sensing device. Additionally, these optical devices can find an application in optical communications as they can also be used as optical filters.

In this thesis, I focus on device engineering on silicon photonics for biosensing applications, with the main advance in detecting large concentrations of molecules and simplifying the experimental setup. There is a great variety of devices that can be realized in silicon photonics, so I mainly focus on two types of devices which are Bragg gratings and rectangular resonators. The author chose these structures to compare the characteristics of traveling wave with standing wave resonators and also to show the results for single- and multi-mode sensors. Light is coupled to both types of devices via a planar waveguide and I provide an in depth optical characterization of the devices and the impact of the different design parameters in the optical spectrum. Furthermore, to demonstrate the performance of the devices in sensing applications, the biotin-avidin protein complex is proposed to evaluate specific binding reactions. In order to close the loop between simulation and experimental characterization, the author uses Waseda University Nanotechnology Research Center, where it is possible to fabricate prototypes of the sensors by using electron-beam lithography and a single reactive ion etching step. Once the prototype has been fabricated, I perform a two-step chemical activation to evaluate specific binding. The structure of the thesis is summarized as follows.

Chapter 1. A comprehensive introduction regarding silicon photonics is given. New research trends are highlighted to discuss the future of silicon photonics while previous research in the laboratory group is used as a starting point. I also introduce the material I will use that is silicon-on-insulator, which is the most commonly used material in silicon photonics. Then, special interest is payed to the simulation tool, as I use the finite difference time domain algorithm to design and evaluate the subsequent devices. Following, the author describes the fabrication procedure to be used to achieve optimal devices, and show the effects that different conditions in the fabrication processes have on the final device. I continue with the description of the experimental setup, which is used throughout the thesis to optically evaluate all the devices. Finally, I identify the main issues that will be addressed in this work.

Chapter 2. In this chapter, I propose, demonstrate and thoroughly characterize a functional fully-etched diffraction grating coupler based on subwavelength size structures to obtain light coupling in and out of the chip. The author begins by introducing shallow-etched diffraction couplers which is a very common structure used to couple light. They have the advantage that they can be placed anywhere on the chip, but require two etching steps. Given the fabrication constraints they need to be fabricated at the same time as the rest of the device. Therefore, fully etched diffraction couplers are designed as they are compatible with the fabrication process and still maintain a high performance. I analyze the effects of changing the period, structure size and fiber tilt angle on the optical characteristics of the coupler and also propose a similar device for TM-polarized light. The obtained efficiencies and bandwidths are comparable to shallow-etched grating couplers. I use these designs as the standard light coupling structure in the following sections. Finally, I briefly introduce another method of coupling light, the SSC, and compare both methods in terms of efficiency, polarization, bandwidth, alignment tolerances and the experimental setup requirements.

Chapter 3. Once it is possible to input light into the chip, I study in detail a device structure that is useful for biosensors and also has a very high relevance in optical communications, the Bragg gratings. This structure can be fabricated in many configurations, ranging from modulating the sidewalls, the cladding, the waveguide core or the top surface. Keeping in mind the fabrication constraints, I focus on the first three configurations. The author first uses sidewall Bragg gratings to characterize the main waveguide parameters, namely, the effective refractive index, group index and loss. Furthermore, to obtain high Q transmission peaks, which are necessary for biosensors, the usage of sidewall Bragg gratings with Fabry-Perot cavities is proposed. The second structure I study is the waveguide-core modulated Bragg gratings that are capable of suppressing the backward propagating light and achieve a very strong coupling coefficient. This structure consists of a two-mode waveguide with conjunction of a photonic crystal and linear tapers. Specific wavelengths are converted from the fundamental mode to the second order mode by the photonic crystal, and then, they are filtered by the linear taper as they return. As the coupling coefficient is strong, a very large stopband is achieved, in the order of 200 nm, and I use a phase shift section to obtain a single transmission peak, with moderate Q factor in this stopband. The device is very compact as only a few number of periods are required due to the strong coupling coefficient. Finally, in this chapter, the cladding modulated Bragg grating is presented, where the periodic modulation of the refractive index is achieved by placing rods close to the waveguide, so only the evanescent field interacts with those rods, and I found that the coupling coefficient is very low.

Chapter 4. In this chapter I introduce a standing wave resonator that is based on a rectangular device. As standing wave resonators have different properties than their travelling wave counterparts they can be used in unique applications. Because the size of the rectangle is much larger than the wavelength to be used, I first study the rectangular resonator from the analytical point of view of ray optics. I can confirm the existence of a standing wave inside the cavity, so that in an add-drop filter configuration, equal amounts of power are coupled outwards from the drop port. Then, I simulate the electrical field inside the cavity using the FDTD algorithm. To input power into the device, I evanescently couple to the resonator with a planar waveguide next to it. As the rectangle is a multimode resonator, I show that the bus waveguide dimensions are very important to only couple to a specific set of resonances. The author calculates the figure of merit called coupling ideality by changing the coupling length and the gap from the bus to the resonator. After experimentally optimizing the device parameters, the symmetry of the device is investigated by proposing an 8 port configuration, where similar waveguides are placed on the four sides of the rectangle. I also fabricate different sizes of rectangles and show their characteristics in terms of the Q value and free spectral range. The same analysis is carried out for TM polarized light, and different results in optimal device parameters are obtained mainly because of the field distribution inside the cavity. The large FSR and high Q values allows the device to be used as a biosensor.

Chapter 5. Proof-of-concept biosensing experiments are conducted with the previously studied devices to compare them in terms of sensitivity, thermal fluctuations and saturation limits. Two main types of experiments are performed, one is for bulk refractive index sensing and the second one is for specific binding sensing. The first one is done by exposing the sensor to different concentrations of NaCl in water with the help of a microfluidic channel. For the second type I use the biotin-avidin complex that has a very high affinity constant. First, I describe the two-step chemical modification process of the sensor, being silanization and activation with NHS-biotin. Then, I subsequently immerse the sensor to different concentrations of avidin or dopamine for specific and un-specific binding, respectively. By tracking the wavelength shift of the resonant peaks, it is possible to calculate the sensitivity of the sensors. Since the devices have been optimized to achieve high Q values, precise measurements are feasible. The tradeoff between Q value, sensing area and sensitivity is discussed. The author found that FSR-free devices are very suitable for applications where large quantities of molecules need to be detected and since no real time measurements are required, it simplifies the experimental setup.

Chapter 6. The thesis is concluded. I systematically study two different types of optical devices made on silicon on insulator, coupled to a planar waveguide with fully etched diffraction gratings. I advanced on a different biosensing application where large concentrations of molecules have to be detected. Depending on the device, they can also function as filters, signal routers and power splitters in optical communications. These devices have a great promise to become part of the fundamental building blocks in silicon photonics.

早稲田大学　博士（理学）　学位申請　研究業績書

(List of research achievements for application of doctorate (Dr. of Science), Waseda University)

氏 名　Manuel MENDEZ ASTUDILLO　印

（As of February, 2018）

種 類 別 (By Type)	題名、　発表・発行掲載誌名、　発表・発行年月、　連名者（申請者含む）(theme, journal name, date & year of publication, name of authors inc. yourself)
論文 ○ Journal (First Author)	M. Mendez-Astudillo, H. Okayama, H. Nakajima, "Silicon optical filter with transmission peaks in wide stopband obtained by anti-symmetric photonic crystal with defect in multimode waveguides" *Opt. Express.*, Vol. 26, No. 2, p. 1841, (2018).
○	M. Mendez-Astudillo, H. Okayama, H. Nakajima, "Evanescently Coupled Rectangular Microresonators in Silicon-on-Insulator with High Q-Values: Experimental Characterization" *Photonics*, Vol. 4, No. 2, p. 34, (2017).
○	M. Mendez Astudillo, H. Takahisa, H. Okayama, H. Nakajima, "Optical refractive index biosensor using evanescently coupled lateral Bragg grating on silicon-on-insulator", *Jpn, J. Appl. Phys.*, Vol. 55, No. 8S3, p. 08RE09, (2016).
関連論文 (共著) Journal Co-author	H. Okayama, H. Takahisa, M. Tsutsui, M. Mendez-Astudillo, H. Nakajima, "One-port ring refractive index sensor with attached sub-ring" *Optical Review*, Vol. 24, No. 1, pp 11-16, (2016).
国際会議 Int. Conf.	M. Mendez-Astudillo, H. Okayama, H. Nakajima "Mach-Zehnder Interferometer with Fabry-Perot Cavities in Silicon-on-Insulator for Biosensing", 22nd Microoptics Conference (MOC'17), Tokyo, Japan. H-5 (November 2017).
	M. Mendez-Astudillo, H. Okayama, H. Nakajima, "Subwavelength-Size Structures on Silicon-on-Insulator as Grating Couplers for Silicon Photonics Applications", NanoScience and Technolgoy, Singapore, F9.11, (October 2016). [invited]
	Ken Fujiwara, Manuel Mendez-Astudillo, Hiroki Takahisa, Hideaki Okayama, Hirochika Nakajima, "Refractive index sensor using optical square cavity on SOI for TM-polarization," 21st Microoptics Conference (MOC' 16), Berkeley, USA, 13C-22 (October 2016).
	M. Mendez-Astudillo, H. Takahisa, K. Fujiwara, H. Okayama, H. Nakajima, "Multimode Rectangular Optical Microcavity for Biomarker Detection Based on Silicon on Insulator", CLEO 2016, San Jose, JW2A.145 (June 2016).
	M. Mendez Astudillo, H. Takahisa, H. Okayama, H. Nakajima, "Densely multiplexed refractive index biosensor using lateral Bragg gratings on SOI", 20th Microoptics Conference (MOC'15), Fukuoka, Japan, H-32 (October 2015).
	H. Takahisa, M. Tsutsui, M. Mendez-Astudillo, H. Okayama, and H. Nakajima, "One port ring refractive index sensor with attached sub-ring," 20th Microoptics Conference (MOC'15), Fukuoka, Japan, H-39 (October 2015).

早稲田大学　博士（理学）　学位申請　研究業績書

(List of research achievements for application of doctorate (Dr. of Science), Waseda University)

種 類 別 By Type	題名、　発表・発行掲載誌名、　発表・発行年月、　連名者（申請者含む）(theme, journal name, date & year of publication, name of authors inc. yourself)
	M. Mendez Astudillo, D. Volkmann, M. Jager "Multiplexed SOI Ring Resonators for Real-Time Protein Detection", 3rd International Conference on Biophotonics, P2.11, Florence, (May 2015)
国内会議 Domestic Conf.	Manuel Mendez-Astudillo, Hideaki Okayama, Hirochika Nakajima, "Multimode Bragg gratings in Silicon-on-Insulator", JSAP 65 Spring Meeting, Waseda University, 17p-A404-13 (March 2018). 宮崎 翔平, Manuel Mendez-Astudillo, 新井 麻由, 岡山 秀彰, 中島 啓幾,「Bragg Grating 型 Si 細線光導波路屈折率センサー」, 第 78 回応用物理学会秋季学術講演会, 7p-PA2-8 (September 2017). 藤原 健, 高久 寛基, Manuel Mendez-Astudillo, 岡山 秀彰, 中島 啓幾,「TM モードの利用による矩形共振器型 SOI 屈折率センサの高感度化」, 第 77 回応用物理学会秋季学術講演会, 15a-P8-12 (2016). M. Mendez-Astudillo, "SOI Ring resonators for Real-Time Protein Detection", International Year of Light Commemoration Symposium, No. 112, University of Tokyo, (April 2015). M. Mendez Astudillo, M. Jager, D. Volkmann, H. Nakajima "Multiplexed SOI Ring Resonators for Biosensing Applications", JSAP 62 Spring Meeting, Tokai University, 13a-A15-9 (March 2015).