1-1-2014

Real-Time High Resolution Integrated Optical Micro-Spectrometer

Sabarish Chandramohan
Wayne State University,

Recommended Citation

Chandramohan, Sabarish, "Real-Time High Resolution Integrated Optical Micro-Spectrometer" (2014). *Wayne State University Theses.* Paper 328.

REAL-TIME HIGH RESOLUTION INTEGRATED OPTICAL MICRO-SPECTROMETER

by

SABARISH CHANDRAMOHAN

THESIS

Submitted to the Graduate School

of Wayne State University,

Detroit, Michigan

in partial fulfillment of the requirements

for the degree of

MASTER OF SCIENCE

2014

MAJOR: ELECTRICAL ENGINEERING

Approved By:

____

Advisor Date

DEDICATION

Dedicated to

My Parents & My wife

ACKNOWLEDGEMENTS

First of all, I would like to express my gratitude to my advisor Dr. Ivan Avrutsky for his advice, guidance and support. I would like to thank Dr. Amar Basu and Dr. Ming-Cheng Cheng for being part of my thesis committee. I thank my wife, Arya Suresh and my parents, Chandramohan and Sudha Chandramohan for the support in all my endeavors. I thank Dr. Pepe Siy and Dr. Syed Mahmud for the advices throughout my MS study. I thank NSF Center for Photonics and Multiscale Nanomaterials (C-PHOM), Material Research Science and Engineering Center Program for the support through grant DMR 1120923.

I would also like to thank my previous colleague Pradeep kumar and my co-colleague Mohammed Hossain for all the help. I thank my friends Santhosh, Gopakumar Kamalakshakurup for all the support and encouragement during my difficult times.

PREFACE

In this thesis, I present my work on a real-time high resolution integrated optical micro-spectrometer based on planar single-mode waveguide grating.

Chapter 1 gives an introduction of different miniature and micro-spectrometers based on planar gratings and other concepts in this field. An overview of different technologies used to display the output of micro-spectrometer is given in this chapter. Applications of micro-spectrometers which motivated me to develop this project is also explained.

Chapter 2 describes the design of the micro-spectrometer. Different components which is used to assemble and realize the micro-spectrometer is explained in this chapter.

Chapter 3 explains the algorithm developed to display the output of micro-spectrometer from the raw image of CMOS sensor. Algorithm is explained in detail. The data processing technique to eliminate the noise is also explained.

Chapter 4 discusses the conclusion of the thesis along with the future developments.

Sincerely,

Sabarish Chandramohan

TABLE OF CONTENTS

LIST OF FIGURES

Chapter 1

Introduction

Micro-spectrometers have been developed based on different platforms and technologies. These platforms include micro-spectrometers based on planar gratings such as planar dispersion grating micro-spectrometers with spherical optics [1-3], and planar imaging grating micro-spectrometers [4-8]. Micro-spectrometers are also developed without diffraction gratings which are integrated filter arrays [9], interferometers [10, 11], photonic crystals [12], Fabry-Perot optical resonators [13], etc. Development of micro-spectrometers using different technologies includes MEMS based [14-16], and Fourier transform based devices [17, 18]. Micro-spectrometers on these platforms and technologies can be developed in different spectral ranges which are visible, ultra-violet and infra-red ranges.

A micro-spectrometer with high resolution of 0.5 nm in the visible spectrum with 35 input optical channels is demonstrated in [4]. Micro-spectrometer with spectral resolutions of 0.2 nm with f = 14 cm and f = 2 cm lenses, and 0.3 nm with f = 1 cm lens is demonstrated in [1]. High spectral resolutions of 0.7nm with aberration correcting planar gratings [3], and devices with several nanometers of spectral resolution in visible and infrared ranges have been reported in [5, 7-18].

Spectroscopy is a massive field whose application is extended to different fields including biosensors, microbiology and chemical sensors [19-21]. These applications needs detection in molecular levels. This motivated to develop an integrated optical device for the spectroscopy of monolayer of molecules or a single molecule as shown in Figure-1.1.

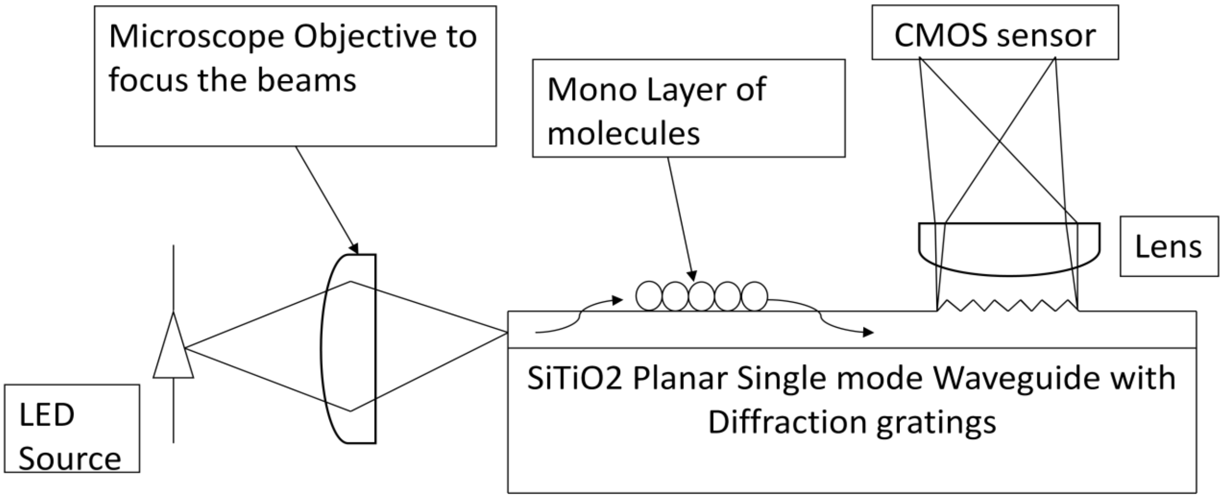


Figure-1.1: Ultimate setup to develop an integrated optical device for the spectroscopy of a monolayer of molecules or a single molecule.

In this study, a real-time integrated planar single-mode waveguide grating micro-spectrometer with high resolution of 0.5 nm in 120 nm wide range of visible spectrum, from 525 nm to 645 nm is demonstrated as shown in Figure-1.2. A CMOS sensor is used for capturing the output image of micro-spectrometer. A f = 1cm lens is used to focus the diffracted monochromatic light onto the CMOS sensor. An algorithm is developed using simple polynomial equation which uses two known reference wavelengths to convert x-pixel numbers of the CMOS sensor to wavelength spectrum. The output of micro-spectrometer in this design has comparatively less noise than usual spectrometric measurements. This design uses built-in matlab functions such as 'findpeaks' [22] to find the input laser peaks and the central pixel numbers for that peaks and 'polyfit' [24] to find the coefficients essential for the calibration of wavelength spectrum.

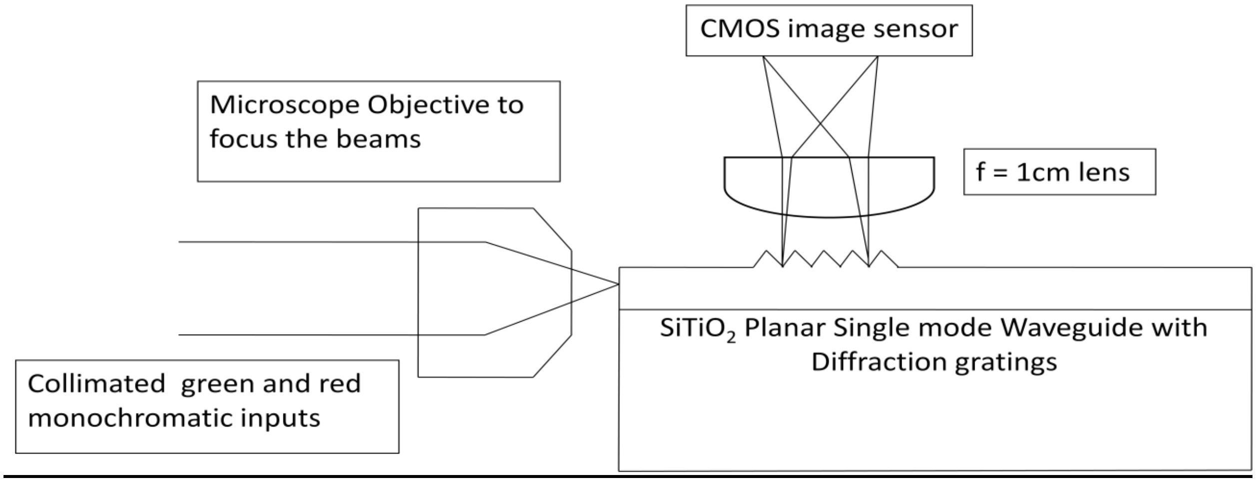


Figure-1.2: Schematic view of a high-resolution integrated optical micro-spectrometer.

This study only discusses the design of a micro-spectrometer which is a preliminary step. With further enhancement of output image processing with appropriate algorithms, the development of very sensitive micro-spectrometer for detection of molecular level signals as shown in Figure-1.1 is achievable.

Chapter 2

Design of Micro-spectrometer

The micro-spectrometer consists of SiTi0_2 planar single-mode waveguide with diffraction gratings [26], and lens to focus the diffracted wavelengths onto the CMOS sensor.

2.1 SiTi0_2 planar single-mode waveguide

The SiTi0_2 planar single-mode waveguide contains the diffraction gratings on a glass substrate (BK7). The refractive index of the waveguide film is 1.77 ± 0.03. The thickness of the film is 170-220 nm. The glass substrate is of length 12mm and width 8mm with a thickness of 0.50mm and refractive index of 1.53. The diffraction grating used has a surface relief structure of 20nm. The grating periodicity is 2400 lines/mm (0.4166 µm). The width of total grating is 2mm. The grooves of the gratings are parallel to the width of the sample. The waveguide edge on the non-coupling side is covered with a thick black paper to block the scattered stray light from the non-coupling edge and glass substrate to reduce the noise level of the spectrometer. Figure -2.1 shows the cross-sectional view of the waveguide.

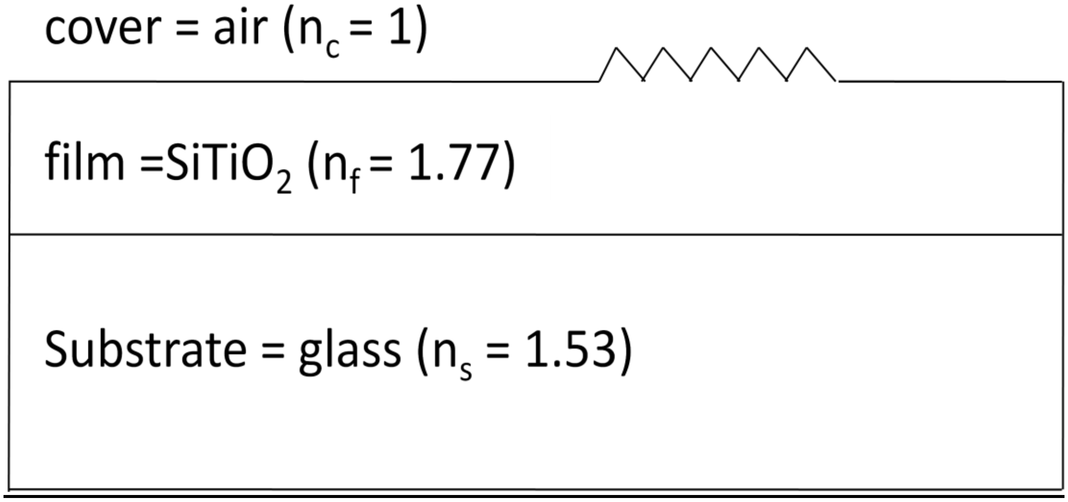


Figure-2.1: Cross-sectional view of SiTi0_2 planar single-mode waveguide.

2.2 Lens

A lens with focal length of 1cm is used to focus the diffracted monochromatic light to the CMOS sensor. Since the monochromatic lights are diffracted at an angle to the normal of the gratings, the lens is placed at the same angle to perfectly focus the diffracted lights onto the sensor. Figure-2.2 shows the focusing lens used. The lens holder is adjusted in the design so that it doesn't restrict fine adjustments for waveguide, microscope objective or the sensor.

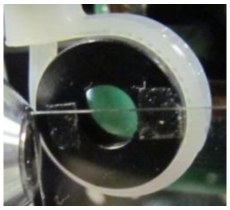


Figure-2.2: Focusing Lens

2.3 Aptina Image Sensor (MT9M032)

The CMOS image sensor used is Aptina MT9M032 monochromatic sensor as shown in Figure-2.3. The sensor area is 3.24mm x 2.41mm. It is 1.6Mp with maximum image size of 1440 x 1080 and having an optical format of 1/4.5 inch (4:3). The output of the sensor is set to maximum bit-size of 12-bit and the filter array format used is Bayer pattern (Bayer-12). The sensor board is attached to a Demo Board of version 2.0 from Aptina which enables the PC connectivity through USB port. The output from the sensor is interfaced to matlab using DevWare [25] (CMOS sensor software).

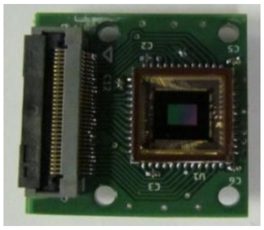


Figure-2.3: Aptina MT9M032 Monochromatic sensor.

2.4 Optical Micro-Spectrometer

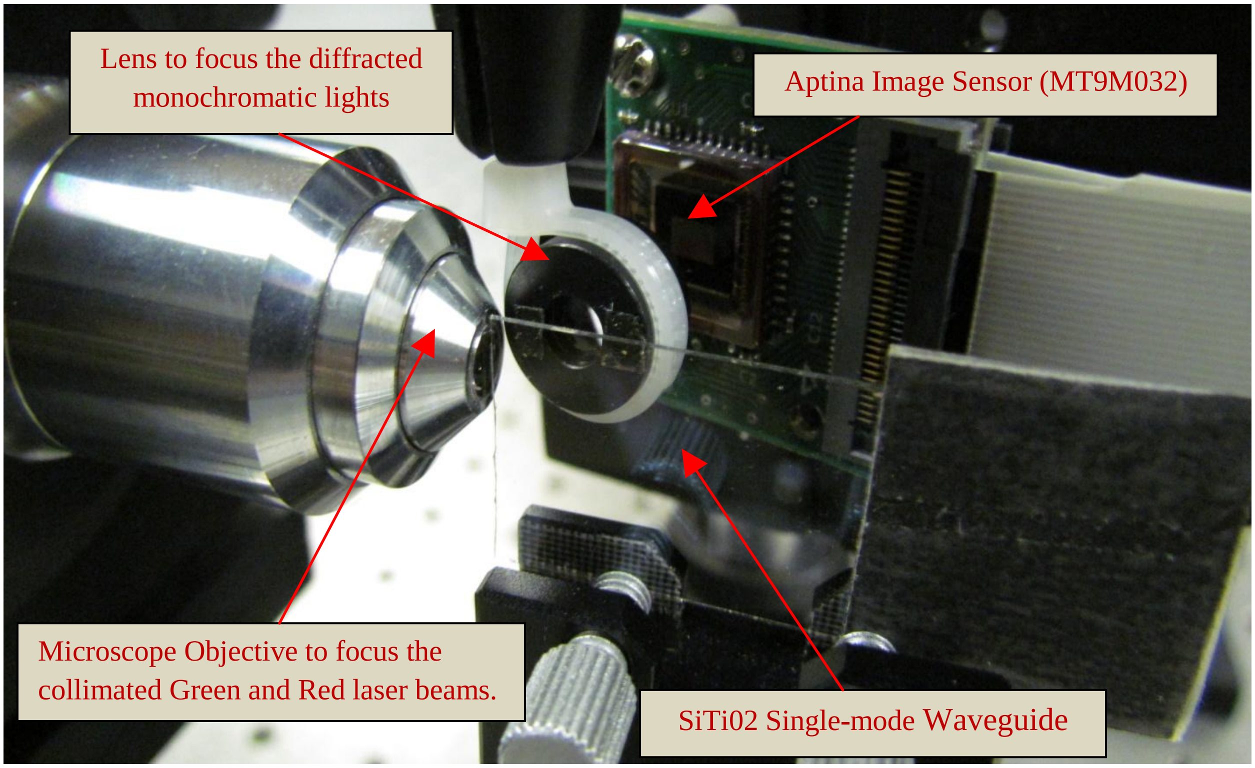


Figure-2.4: Optical micro-spectrometer.

Figure-2.4 shows the optical micro-spectrometer. A beam splitter is used to combine the green (532 nm) and red (632.8 nm) monochromatic laser beams. Collimators with same Numerical Aperture (NA) are used at both ends of a single mode fiber to couple the combined monochromatic laser beams. The collimated monochromatic light out coupled by the fiber is focused by a microscope objective onto the edge of the waveguide. A 3-way translational stage is used to mount the waveguide which allows the adjustment in X, Y and Z directions to the input collimated light source focused by the microscope objective. The microscope objective is also adjustable in X, Y and angular directions which allows additional adjustment to move the focus of the input collimated light. Figure-2.5 shows the monochromatic lights propagating through the waveguide.

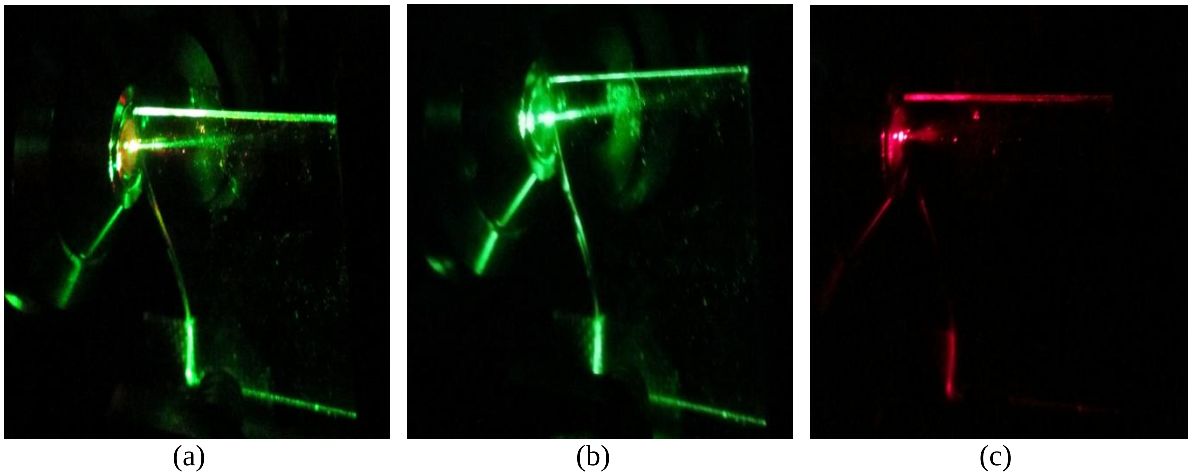

(a) (b) (c)

Figure-2.5: (a) Collimated green and red monochromatic lights propagating through the waveguide (b) propagation of only green monochromatic input (c) propagation of only red monochromatic input.

Laser beams with large power and very sensitive CMOS image sensor accounts for attenuation of the beams before it is coupled to the fiber. The green and red laser beams have different output powers which necessitates separate attenuation. The collimated green and red monochromatic laser beams after hitting the gratings gets diffracted at different angles and is captured using CMOS image sensor. The red monochromatic light is diffracted at a smaller angle with normal to the plane of the gratings due to its larger wavelength and gets focused towards the lower pixel number region of CMOS image sensor and green monochromatic light is diffracted at larger angle and is focused to the higher pixel number region. Figure-2.6 shows the diffracted green and red monochromatic lights captured by the CMOS image sensor. The diffracted lights are shaped as arcs as shown since the light guided through the waveguide diverges.

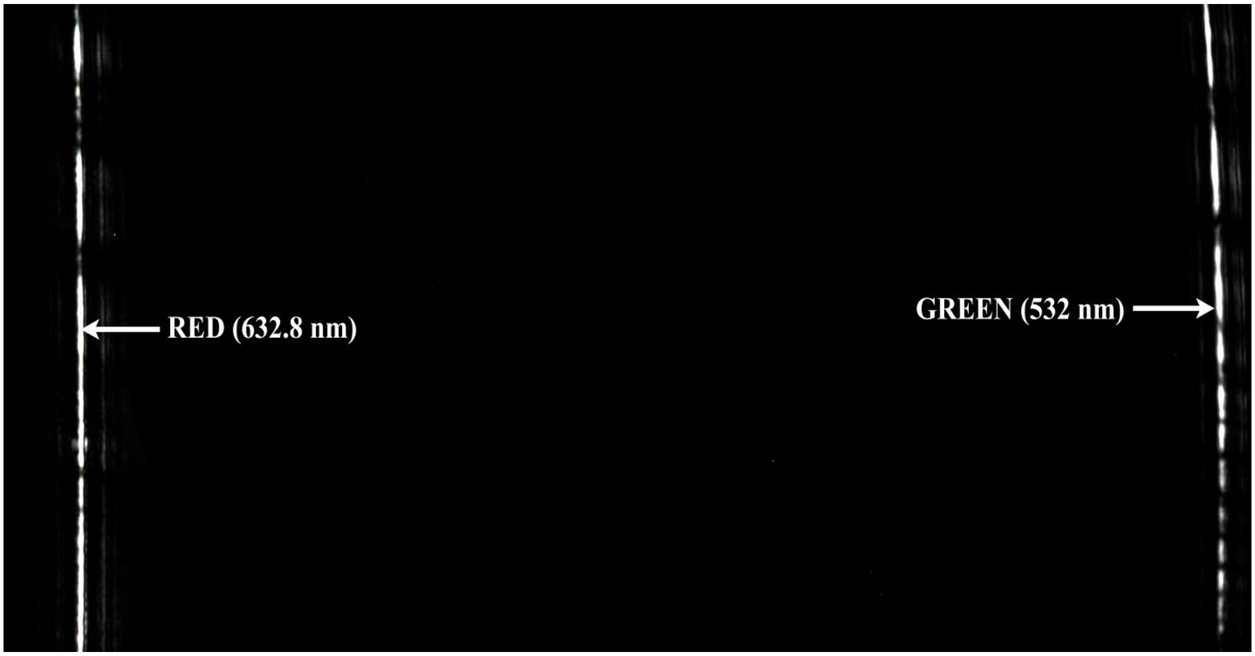
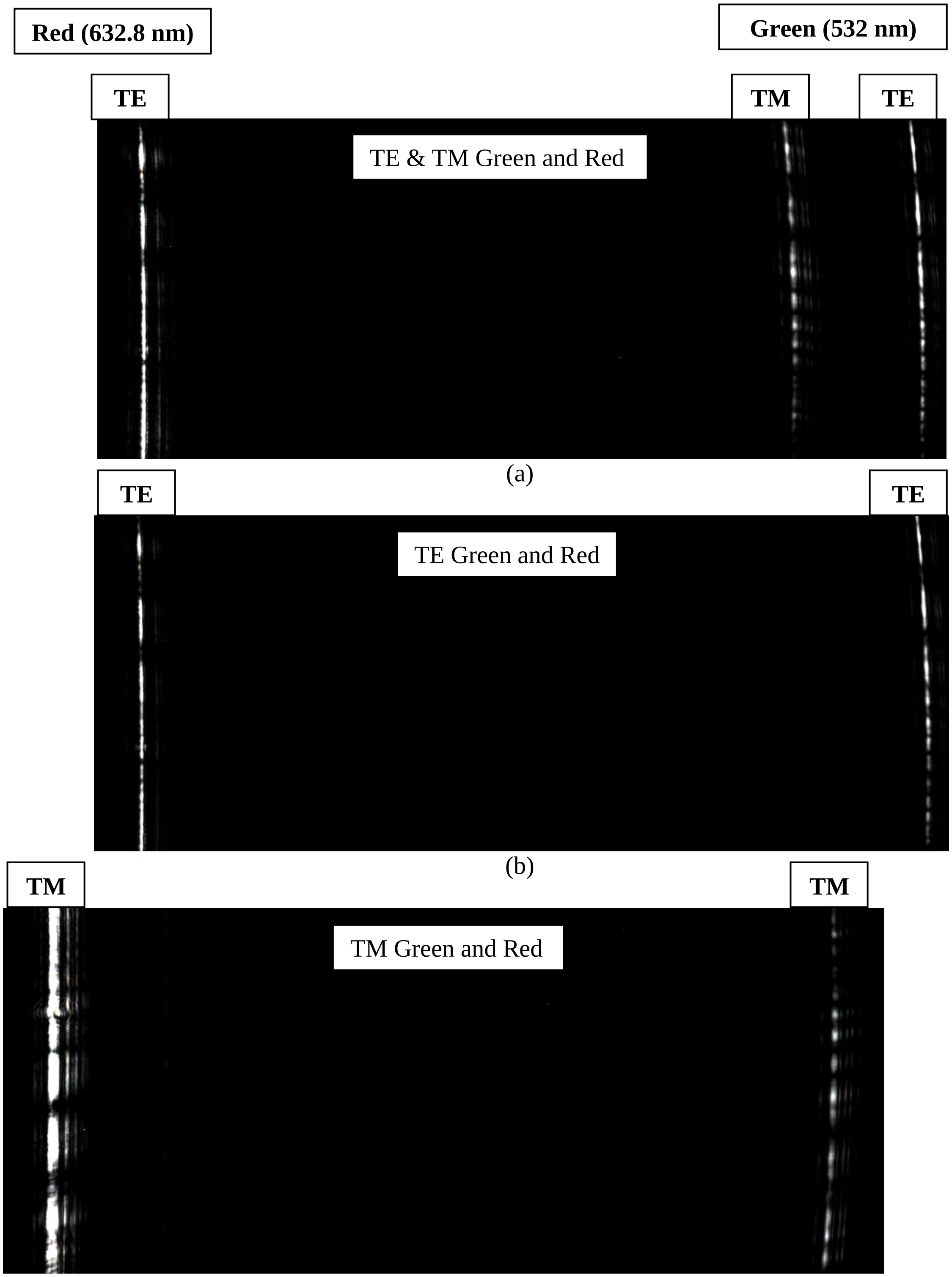


Figure-2.6: Diffracted monochromatic lights captured by CMOS image sensor.

The polarizer was placed before the microscope objective to verify whether the images captured by CMOS image sensor is the guided light and not the scattered stray light from the glass substrate. As shown in Figure-2.7 (a), (b) and (c), by setting the polarizer at different angles, only TE or TM modes, or both the modes together can be excited. The location of the diffracted light on the sensor is polarization dependent. This concludes that the diffracted light captured by the CMOS image sensor is due to the guided mode. TM component of red monochromatic input is captured by shifting the image sensor towards the left as shown in Figure-2.7 (c).Only TE mode is chosen in this work.



(a)

(b)

(c)

Figure-2.7: (a) Green and red TE&TM monochromatic inputs, (b) TE-polarized monochromatic inputs, (c) TM-polarized monochromatic inputs. The image sensor is shifted towards left to capture TM-polarized inputs.

Chapter 3

Algorithm to display the output of micro-spectrometer

A real-time image processing algorithm is developed using matlab to display the output of micro-spectrometer. The algorithm is developed for working in two modes, which are the calibration mode, and the measurement mode. The output of CMOS image sensor is a matrix of light intensity versus x- and y-pixel numbers of the CMOS image sensor. The calibration mode uses a simple quadratic equation to convert the x-pixel number scale to the wavelength spectrum.

3.1 Calibration Mode

Calibration mode converts the x-pixel numbers of CMOS image sensor to the corresponding wavelength spectrum. The calibration mode works in two phases namely image acquisition phase and conversion phase. The image acquisition phase gets the raw images from DevWare with the help of invoke function in activexserver [23]. The conversion phase helps to find the central pixel numbers which is used to find the parameters that define the relation of wavelength and pixel numbers.

3.1.1 Image Acquisition Phase

The Image Acquisition Phase takes raw images from the CMOS sensor with the help of invoke function in activexserver from Devware (CMOS Sensor Software).

3.1.2 Conversion Phase

A bright y-pixel in the incoming raw image is selected as shown in Figure-3.1.

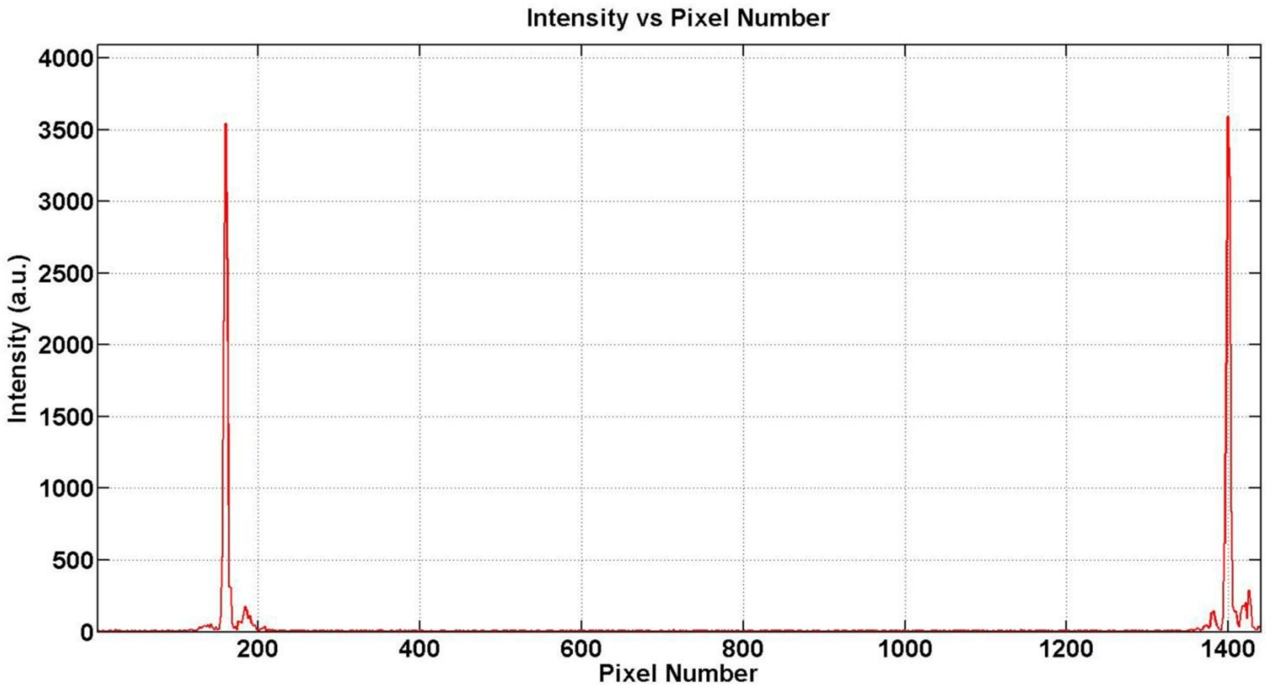


Figure-3.1: Intensity versus Pixel number for a bright y-pixel

The 'findpeaks' function in matlab gives the maximum intensities of green and red monochromatic inputs and x-pixel numbers for those maximum intensities. A polynomial relation is formulated between the known reference wavelengths, λ_1 and λ_2 and central pixel numbers, x_1 and x_2 given by Eq. (1) and Eq. (2).

$$\lambda_1 = a x_1^2 + b x_1 + c \quad (1)$$

$$\lambda_2 = e x_2^2 + f x_2 + g \quad (2)$$

Then 'polyfit' function of Matlab is used to find the values of a, b, c and e, f, g. These coefficients are averaged to find the values of m, n, o given by Eq. (3) , Eq. (4) and Eq. (5).

$$m = (a + e) / 2 \quad (3)$$

$$n = (b + f) / 2 \quad (4)$$

$$o = (c + g) / 2 \quad (5)$$

Then these coefficients are substituted in the polynomial relation given by Eq. (6).

$$\lambda = mx^2 + nx + o \qquad (6)$$

Thus from Eq. (6), the wavelength spectrum is calibrated by substituting the x-pixel numbers which will give a matrix of 1440 wavelengths corresponding to 1440 x-pixels of the CMOS image sensor as shown in Figure-3.2.

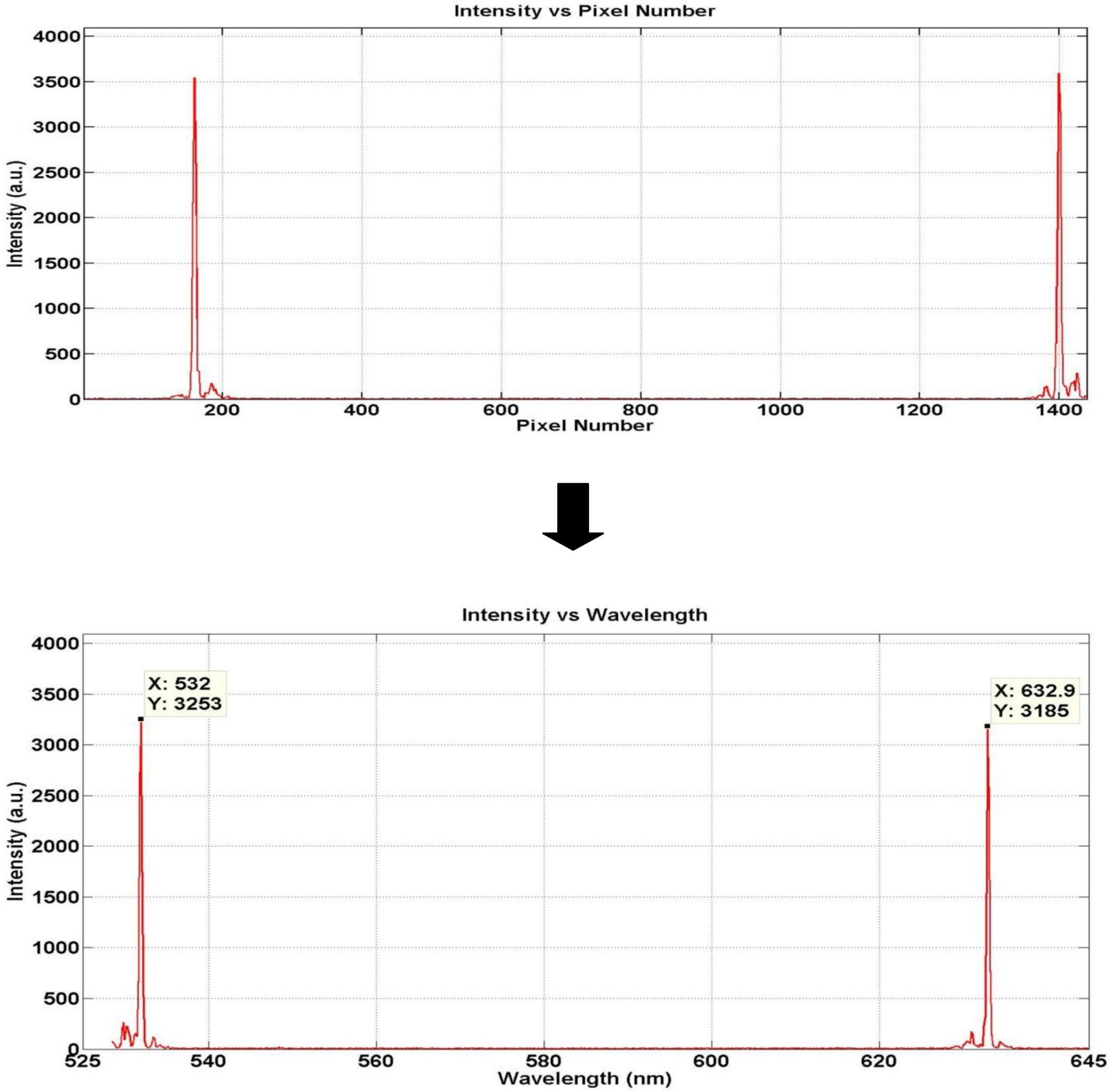


Figure-3.2: Conversion from x-pixel number of CMOS sensor to Wavelength Spectrum

3.1.3 Output of micro-spectrometer

The output of micro-spectrometer is shown in Figure-3.3. The spectral resolution of the micro-spectrometer is calculated by Full-Width at Half Maximum (FWHM). FWHM calculated for both green and red monochromatic input is 0.5 nm which defines the spectral resolution of the micro-spectrometer as 0.5nm in a 120 nm wide range of visible spectrum, from 525 nm to 645 nm.

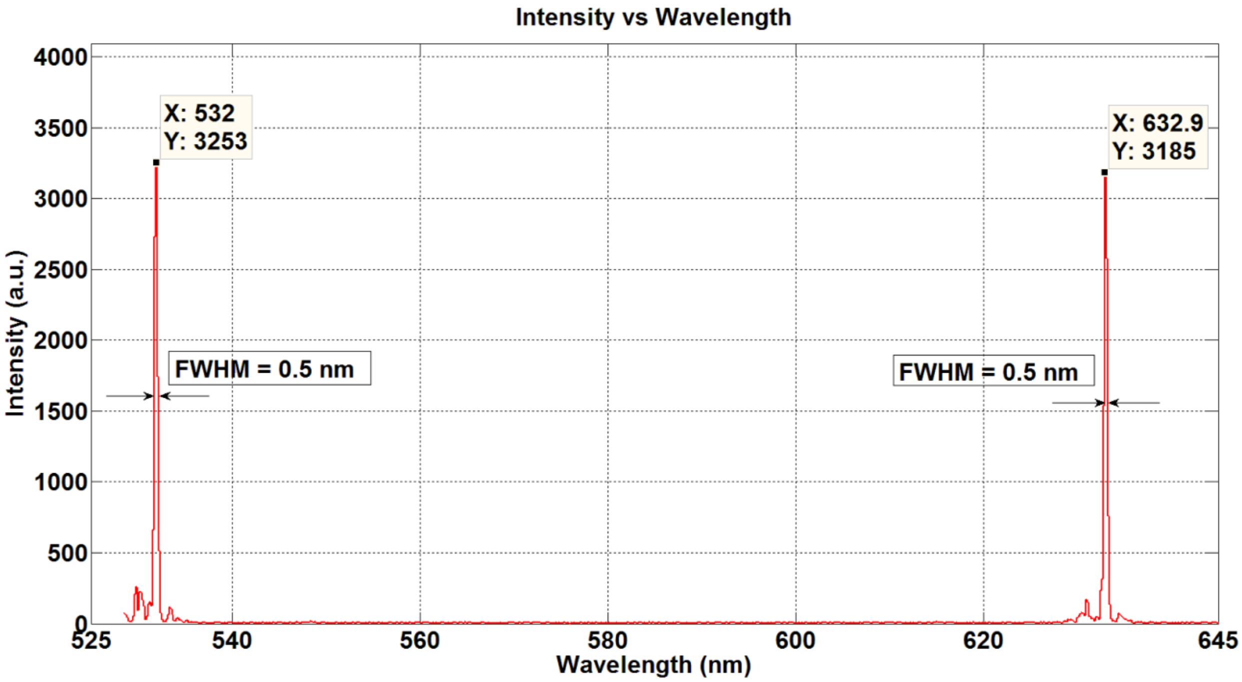


Figure-3.3: Output of micro-spectrometer, Intensity versus Wavelength

3.2 Measurement Mode

Measurement mode is used when the micro-spectrometer is already calibrated once. Measurement mode uses the calibrated data to provide the real-time output. The calibration mode saves the wavelength spectrum calculated from the x-pixel numbers of the CMOS image sensor in a mat file. The measurement mode uses these data to display the output of the micro-spectrometer.

Chapter 4

Conclusion

A real-time high resolution integrated optical micro-spectrometer with a spectral resolution of 0.5 nm is demonstrated. The real-time display of output allows to capture the change in the output at once thereby facilitating the micro-spectrometer to be used in real-time devices. The use of built-in functions of matlab in this design helped to develop a simple algorithm for real-time image processing to display the output of the micro-spectrometer. Two reference wavelengths 532 nm and 632.8 nm are used in the algorithm to calibrate wavelength spectrum from the x-pixel numbers of the CMOS image sensor. The output of the micro-spectrometer in this design has less noise as the intensities of the reference monochromatic inputs are attenuated which helped in reducing the scattered stray light from the glass substrate.

Future development includes further development of this algorithm to curve fit the data using data processing algorithms such as least square algorithms which allows for the accurate extraction of central pixel numbers. Suitable mapping algorithm can be developed to map the wavelength spectrum to the set of x-pixel numbers for the entire arc in a curved coordinate system instead of using a simple polynomial equation. An algorithm can be developed to average the intensity along the arcs corresponding to monochromatic inputs instead of selecting a single y-pixel of interest which enhances the sensitivity of this device thereby realizing an integrated optical device suitable for detection of signals from monolayer of molecules or a single molecule.

REFERENCES

[1] Kalyani Chaganti, Ildar Salakhutdinov, Ivan Avrutsky, Gregory W. Auner, "A simple miniature optical spectrometer with a planar waveguide grating coupler in combination with a Plano-convex lens", Optics Express, Vol. 14, No. 9, 4064-4072 (2006).

[2] I. Avrutsky, K. Chaganti, I. Salakhutdinov, and G. Auner, "Optical Micro-Spectrometer with Sub-Nanometer Resolution", NSTI-Nanotech 2006, www.nsti.org, Vol. 3, 328-331 (2006).

[3] Semen Grabarnik, Arvin Emadi, Huaiwen Wu, Ger de Graaf, and Reinoud F. Wolffenbuttel, "High-resolution micro spectrometer with an aberration-correcting planar grating", Applied Optics, Vol. 47, No. 34, 6442-6447 (2008).

[4] I. Avrutsky, K. Chaganti, I. Salakhutdinov, and G. Auner, "Concept of a miniature optical spectrometer using integrated optical and micro-optical components", Applied Optics, 45, 7811-7817 (2006).

[5] Robert Brunner, Matthias Burkhardt, Klaus Rudolf, and Nico Correns, "Microspectrometer based on holographically recorded diffractive elements using supplementary holograms", Optics Express,Vol.16, Issue 16, 12239-12250 (2008).

[6] S. Grabarnik, R. Wolffenbuttel, A. Emadi, M. Loktev, E. Sokolova and G. Vdovin, "Planar double-grating microspectrometer", Optics Express, Vol. 15, No. 6, 3581-3588 (2007).

[7] Semen Grabarnik, Arvin Emadi, Elena Sokolova, Gleb Vdovin, and Reinoud F. Wolffenbuttel, "Optimal implementation of a microspectrometer based on a single flat diffraction grating", Applied Optics, Vol. 47, Issue 12, 2082-2090 (2008).

[8] Shogo Ura, Fumikazu Okayama, Koichi Shiroshita, Kenzo Nishio, Takahiro Sasaki, Hiroshi Nishihara, Tsutom Yotsuya, Masato Okano, and Kazuo Satoh, "Planar Reflection Grating Lens for Compact Spectroscopic Imaging System", Applied Optics, Vol.42, No.2, 175-180 (2003).

[9] Shao-Wei Wang, Changsheng Xia, Xiaoshuang Chen, Wei Lu, "Concept of a high-resolution miniature spectrometer using an integrated filter array", Optics Letters, Vol. 32, Issue 6, pp. 632 - 634 (2007).

[10] Miroslaw Florjanczyk, Pavel Cheben, Siegfried Janz, Alan Scott, Brian Solheim, and Dan-Xia Xu, "Multiaperture planar waveguide spectrometer formed by arrayed Mach-Zehnder interferometers", Optics Express, Vol.15, Issue 26, 18176-18189 (2007).

[11] Gaël Latour, Julien Moreau, Mady Elias and Jean-Marc Frigerio, "Micro-spectrometry in the visible range with full-field optical coherence tomography for single absorbing layers", Elsevier, Optics Communications, Vol.283, Issue 23, 4810–4815 (2010).

[12] Babak Momeni, Ehsan Shah Hosseini, and Ali Adibi, "Planar photonic crystal micro-spectrometers in silicon-nitride for the visible range", Optics Express, Vol. 17, No. 19, 17060-17069 (2009).

[13] J. H. Correia, M. Bartek and R. F. Wolffenbuttel, "High-selectivity single-chip spectrometer in silicon for operation in visible part of the spectrum", IEEE Transactions on Electron Devices, Vol.47, Issue 3, 553 - 559 (2000).

[14] R. F. Wolffenbuttel, "MEMS-based optical mini- and microspectrometers for the visible and infrared spectral range", Journal of Micromechanics and Microengineering ,Vol.15, No.7, S145 - S152 (2005).

[15] Reinoud F. Wolffenbuttel, "State-of-the-Art in Integrated Optical Microspectrometers", IEEE Transactions on Instrumentation and Measurement, Vol. 53, No. 1, 197-202 (2004).

[16] S. Grabarnik, A. Emadi, H. Wu, G. de Graaf and R.F. Wolffenbuttel, "Microspectrometer with a concave grating fabricated in a MEMS technology", Elsevier, Procedia Chemistry, Vol.1, Issue 1, 401–404 (2009).

[17] Omar Manzardo, Hans Peter Herzig, Cornel Marxer and Nico F.de Rooij, "Miniaturized time-scanning Fourier Transform Spectrometer based on silicon technology", Optics Letters, Vol. 24, No.23,1705-1707 (2007).

[18] Vladislav Jovanov, Jordan Ivanchev, and Dietmar Knipp, "Standing wave Spectrometer", Optics Express, Vol. 18, No. 2, 426-438 (2010).

[19] Dietmar Sander, Oliver Blume, and Jörg Möller, "Microspectrometer with slab-waveguide transmission gratings", Applied Optics, Vol. 35, No. 21, 4096-4101 (1996).

[20] Christina. P. Bacon, Yvette Mattley, and Ronald DeFrece, "Miniature spectroscopic instrumentation: Applications to biology and chemistry", Review of Scientific Instruments, Vol.75, No.1, 1-16 (2004).

[21] Gaylin. M. Yee, Nadim. I. Maluf, Paul. A. Hing, Michael Albin, and Gregory. T.A. Kovacs, "Miniature spectrometers for biochemical analysis", Elsevier, Sensors and Actuators, Vol.58, Issue 1, 61-66 (1997).

[22] *Signal Processing Toolbox for use* with MATLAB®, © copyright 1988 - 2001 by The MathWorks, Inc.

[23] External Interfaces, MATLAB®, © COPYRIGHT 1984–2013 by The MathWorks, Inc.

[24] http://www.mathworks.com/help/matlab/ref/polyfit.html, MATLAB®, © COPYRIGHT 1984 – 2013 by The MathWorks, Inc.

[25] https://www.aptina.com/support/Devsuite.jsp, DevWare, © 2008 - 2013 Aptina Imaging Corporation.

[26] http://www.owls-sensors.com/sensorchip_ow2400, Optical Waveguide Grating Coupler, © 2000 - 2013 MicroVacuum Ltd.

ABSTRACT

REAL-TIME HIGH RESOLUTION INTEGRATED OPTICAL MICRO-SPECTROMETER

by

SABARISH CHANDRAMOHAN

AUGUST 2014

Advisor: Dr. Ivan Avrutsky

Major: Electrical Engineering

Degree: Master of Science

A real-time integrated planar single-mode waveguide grating micro-spectrometer with high resolution of 0.5 nm in 120 nm wide range of visible spectrum, from 525 nm to 645 nm is demonstrated. A CMOS sensor is used for capturing the output image of micro-spectrometer. A f = 1cm lens is used to focus the diffracted monochromatic light onto the CMOS sensor. An algorithm is developed using simple polynomial equation which uses two known reference wavelengths to convert x-pixel numbers of the CMOS sensor to wavelength spectrum. The output of micro-spectrometer in this design has comparatively less noise than usual spectrometric measurements. This design uses built-in matlab functions such as 'findpeaks' to find the input laser peaks and the central pixel numbers for that peaks and 'polyfit' to find the coefficients essential for the calibration of wavelength spectrum.

AUTOBIOGRAPHICAL STATEMENT

Sabarish Chandramohan received his Bachelor of Technology in Electronics and Communication Engineering from University of Kerala, Kerala, India in May 2006. He worked as L1-engineer (Access Corporate NOC) and WiMAX implementation engineer at Tata Communications Limited. His projects includes Industrial Access Controller Using 89C51, Microcontroller based Echo-Simulator , Tactile Sensing Arrays For Humanoid Robots etc. He is now pursuing his PhD in electrical engineering at Wayne State University under the guidance of Dr. Ivan Avrutsky. He is a member of Optical Society of America and IEEE Signal Processing Society and also was a member of Microwave Society and COMSOC of IEEE. He is expected to graduate Master of Science in August 2014.