Investigation of long-period gratings for sensor applications

Tan, Eddie Khay Ming

2007

Tan, E. K. M. (2007). Investigation of long-period gratings for sensor applications. Doctoral thesis, Nanyang Technological University, Singapore.

<https://hdl.handle.net/10356/46936>

<https://doi.org/10.32657/10356/46936>

Nanyang Technological University

Downloaded on 26 Apr 2023 21:37:34 SGT

Investigation of Long-Period Gratings for Sensor Applications

Tan Khay Ming, Eddie

School of Electrical and Electronic Engineering

A thesis submitted to the Nanyang Technological University
in fulfilment of the requirement for the degree of
Doctor of Philosophy

2007

TA
1815
T161
2007

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research and has not been submitted for a higher degree to any other University or Institution.

30th March 2007

Tan Khay Ming, Eddie

ACKNOWLEDGEMENTS

This work has come a long way and it will not be possible without the support of many people. With this opportunity, I would therefore like to express my greatest appreciation towards them for their support and guidance they have given to me for the past 4 years.

First, I would like to thank my supervisor, Dr. Tjin Swee Chuan, for his encouragement and guidance. I am also grateful to my co-supervisor, Prof. Soh Chee Kiong, for all the supports and guidance during the work in the School of Civil and Environmental Engineering. I would also like to thank Dr. Martin Ang Tze Wei for his advices and guidance.

I would like thank my colleagues, Benjamin Tay, Lipi and Rupali, for the continual encouragement during those problematic days. Without them, work here is less enjoying and meaningful. A special thank goes to Benjamin also for his support during our technical discussion and brain storming sessions. We had the great findings especially for the case of gelatine-coated LPG high relative humidity sensor in chapter 6.

I would also wish to thank Daniel Gonzalez Fernandez of Photonics Engineering Group, Departamento TEISA, University of Cantabria, Spain, for the fruitful discussions pertaining to the theoretical portion for the embedded LPG bending sensor in chapter 4. It was a great technical discussion via email.

I would like to express my appreciation to Prof. Paul Yager from University of Washington, for providing invaluable information about the structure of gelatin. It has

contributed greatly in the chapter 4 on the refractive index measurement and SEM measurement experiments pertaining to the gelatin-coated LPG relative humidity sensor. I would like to thank Mr. Ong Biow Hiem and Miss Sze Jia Yin for their help in these measurements.

Beside colleagues and friends, there is a special group of people I would like to express my greatest appreciation. They are the laboratory technicians; Ms. Yvonne Yee, Ms. Seet, Mr. Desmond Lim, Ms. Debbie, Ms. Poh Chee, Mr. Chow, Mr. Clarence Tan and Mr. Yong. Without their assistance, my experiments would not be possible.

Last but not least, my greatest gratitude goes to my family members. I would like to thank them for their continual encouragement and understanding. Without them, I would not be able to walk this far. Among my family members, the person I really want to thank is my fiancée, Stella Voo. Thank you for all the patience and advices you have given me for these years and therefore I would like to dedicate this thesis especially to you.

Thank you.

TABLE OF CONTENT	PAGE
Acknowledgement.....	i
Table of content.....	iii
Author’s Publications and Interview.....	vi
Abstract.....	viii
List of Figures.....	x
List of Tables.....	xvi
List of Acronyms.....	xvii
 Chapter 1: Introduction	
1.1 Introduction.....	1
1.2 Research objectives and contributions.....	18
1.3 Dissertation Outline.....	19
 Chapter 2: Fundamental of Long Period Grating	
2.1 Introduction.....	22
2.2 Mode Coupling in Optical Fibers.....	23
2.3 Fiber Bragg Gratings.....	31
2.3.1 Phase Matching Condition.....	32
2.3.2 Principle of Operation.....	34
2.4 Long Period Gratings.....	39
2.4.1 Phase Matching Condition.....	39
2.4.2 Principle of Operation.....	41
2.4.3 Characteristic of Long Period Gratings.....	44
2.5 Effects of External Perturbation on Long Period Gratings.....	55
2.5.1 Temperature on Long Period Grating.....	55
2.5.2 Strain on Long Period Grating.....	58
2.5.3 External Refractive Index on Long Period Grating.....	60
 Chapter 3 Fabrication of Long Period Gratings	
3.1 Introduction.....	66
3.2 Fabrication Techniques.....	66
3.2.1 UV-Laser Amplitude Mask Technique.....	66

3.2.2	CO ₂ Laser Technique.....	71
3.2.3	Femtosecond Laser Pulse Technique.....	75
3.2.4	Electric Arc Technique.....	77
3.2.5	Corrugated Etching Technique.....	78
3.3	Problem with Hydrogen-loaded Long Period Grating.....	81
3.4	Annealing of Long Period Grating.....	86

Chapter 4 Application of Embedded Long Period Gratings (ELPG) as Bending Sensor

4.1	Introduction.....	91
4.2	Experimental setup.....	91
4.2.1	Carbon-fiber composite.....	91
4.2.2	Embedding process.....	94
4.3	Results and discussions.....	102
4.3.1	Response of ELPG to bending.....	103
4.3.2	Sensor performance characterizations.....	111
4.4	Bending direction measurement.....	116
4.5	Simultaneous measurement of bending and temperature.....	119
4.5.1	Background theory.....	120
4.5.2	Results and discussions.....	122

Chapter 5 ELPG for dynamic gain equalization in erbium-doped fiber amplifier

5.1	Introduction.....	128
5.2	Experimental setup.....	131
5.3	Results and discussion.....	132

Chapter 6 High Relative Humidity Measurements Using Gelatin-Coated Long-Period Grating Sensor

6.1	Introduction.....	138
6.2	Coatings.....	138
6.3	Experimental setup.....	141
6.4	Results and discussions.....	143

	Investigation of LPG for sensor applications
6.4.1	Phenomenon.....149
6.4.2	Sensor performance characterizations.....144
6.5	Optimizing sensitivity.....150
 Chapter 7 Conclusion and recommendations	
	Conclusion.....167
	Recommendations for future work.....170
	 Reference.....172

AUTHOR'S ACHIEVEMENTS

INTERVIEW

1. Interview by Ms.Archana Jayarajah from Technical Insights division of Frost & Sullivan (www.ti.frost.com) on the High relative humidity measurements using gelatin coated long-period grating sensors published in Science Direct 2005. The article is published on the 31st Dec 2005 under “**Advanced Sensor Technologies for Industrial Automation and Process Control**”.

JOURNAL

1. N. Ni, C.C. Chan, K.M. Tan, S.C. Tjin and X.Y. Dong, “Broad-band EDFA gain flattening by using an embedded long-period fiber grating filter”, Optics Communications, volume 271, 2007, pp. 377–381.
3. K. M. Tan, C. C. Chan, S. C. Tjin and X. Y. Dong, “Embedded long-period fiber grating bending sensor”, Sensors and Actuators A: Physical, volume 125, issue 2, 2005, pp 267-272.
4. Khay Ming Tan, Chia Meng Tay, Swee Chuan Tjin, Chi Chiu Chan, Harianto Rahardjo, “High Relative Humidity Measurements Using Gelatin Coated Long-Period Grating Sensors”, Sensors and Actuators B: Chemical, Volume 110/2, 2005, pp 335-341.
5. C. M. Tay, K. M. Tan, S. C. Tjin, C. C. Chan, N. Q. Ngo, X. Y. Dong, “A high-resolution tunable fiber Bragg grating filter”, Microwave and Optical Technology Letters, Volume 42, Issue 2, 2004, pp 89-92.
6. C. M. Tay, K. M. Tan, S. C. Tjin, C. C. Chan, H. Rahardjo, “Humidity sensing using plastic optical fibers”, Microwave and Optical Technology Letters, Volume 43, Issue 5, 2004, pp 387-390.

CONFERENCE

1. Jian Sun, ChiChiu Chan, Na Ni, KhayMing Tan, XinYong Dong, Ping Shum, "Application of an Artificial Neural Network for Simultaneous Measurement of Bending Curvature and Temperature with Long Period Fiber Gratings," conference on Optical Fiber Sensors 2006.
2. Nina, C. C. Chan, K. M. Tan and S. C. Tjin, "Erbium doped fiber amplifier gain flattening by using an embedded long period grating", Proc. SPIE Vol. 5998, 2005, pp 59980P-1 – 59980P-7, Boston USA.
3. K. M. Tan, S. C. Tjin, C. C. Chan, Lipi Mohanty, C. M. Tay, "High relative humidity sensing using gelatin-coated long period grating", Proceedings of SPIE Vol. 5855, pp. 375-378.
4. Chi Chiu Chan, Khay M. Tan, Chia M. Tay, and Swee C. Tjin, "Bending measurement using embedded long-period fiber gratings", Proc. SPIE Int. Soc. Opt. Eng. 5590, 2004, pg 96, Philadelphia USA.
5. Chi Chiu Chan, Khay M. Tan, Chia M. Tay, and Swee C. Tjin, "Simultaneous measurement of curvature and temperature for LPG bending sensor", Proc. SPIE Int. Soc. Opt. Eng. 5590, 2004, pg 105, Philadelphia USA.
6. Chia M. Tay, Khay M. Tan, Swee C. Tjin, Chi Chiu Chan, and Harianto Rahardjo, "Humidity sensing using plastic optical fibers", Proc. SPIE Int. Soc. Opt. Eng. 5590, 2004, pg 77, Philadelphia USA.
7. Chia M. Tay, Khay M. Tan, Swee C. Tjin, Chi Chiu Chan, Nam Quoc Ngo, and Xinyong Dong, "High-resolution tunable fiber Bragg grating filter", Proc. SPIE Int. Soc. Opt. Eng. 5590, 2004, pg 128, Philadelphia USA.
8. The Use of Fibre Optics in Bond Strength Testing of Composite Resin. (8 out of 50 in the competition for the 14th Annual Scientific Meeting organised by SGH, on the 26 and 27 Sept 2003.

ABSTRACT

Long period fiber grating or LPG sensor has been gaining popularity due to its sensitivity to numerous perturbations such as temperature, strain and refractive index. The LPG has an advantage over other optical fiber sensors for refractive index sensing since the cladding region of the optical fiber, with LPG, is not required to be etched away in order to gain access to the evanescent field. Since the cladding modes propagate in the cladding within the LPG region of the optical fiber. The advantage is that the structural integrity of the optical fiber remains intact as compared to other optical fiber refractive index sensors with cladding etched away. Currently, a LPG sensor converts a measurand into wavelength. To interrogate the information would require expensive and complicated wavelength interrogation system. This will increase the overall system cost for industrial applications. In addition, other perturbations such as temperature and strain will affect the LPG wavelength, compromising the accuracy of the results. The aim of this research was the investigation of LPG for sensing applications such that the output from the LPG sensors is intensity-based instead of wavelength-based.

Intensity-based LPG sensor requires its resonance dip or coupling strength to change with external perturbation of interest. Two intensity-based LPG sensors were developed and characterized. They were embedded LPG (ELPG) bending sensor and gelatin-coated LPG high relative humidity sensor. Embedding LPG in carbon-fiber composite material not only provides protection to the LPG, it was found experimentally that the ELPG responds to bending by changing its coupling strength with bending while its resonance wavelength remains unchanged. This was due to the matrix in the carbon-fiber composite which has a refractive index higher than that of the optical fiber cladding refractive index. That causes a change in the cladding mode

field with bending, which affected the LPG coupling strength. Characterization of the ELPG yielded that sensor responded linearly to bending with a sensitivity of 5.065 dB/m^{-1} . The results were highly repeatable at 98.1 % and the sensor exhibited low hysteresis. In addition, using ELPG for dynamic equalization of Erbium-doped fiber amplifier's gain spectrum was also proposed and demonstrated with satisfactory results.

Employing the gelatin-coated LPG for humidity sensing found that the sensor responded very well to high relative humidity (RH) between 90 %RH and 99 %RH. This novel environmental optical fiber-based sensor addresses current problems associated with conventional electrical-based humidity sensors. Experimental data showed that the cladding mode's resonance dip or coupling strength of the gelatin-coated LPG sensor changes with different level of high RH. An explanation was proposed that relates the variations in the LPG coupling strength with the change of the gelatin coating refractive index at different humidities. This is true since the refractive index of the gelatin is closer to but lower than that of cladding. Characterizations of the sensor's performance showed a near linear response of the gelatin-coated LPG to humidity at a sensitivity of 0.833 %RH/dBm . The results were 99.71 % repeatable. The sensor also exhibited low hysteresis error and good temporal stability. Experiment on factors affecting the sensor's performance showed that the sensor's performance degraded with thicker coating and at a lower cladding mode.

In this project, intensity-based LPG sensors have been made possible with the demonstration of modifying mode coupling characteristics, between the cladding mode and the fundamental core mode, using surrounding external medium having a

refractive index that is close to and greater than the refractive index of the optical fiber cladding. The intensity-based LPG sensors reduce the cost and complexity of using wavelength-based interrogation systems which is an advantage for industrial applications.

<u>LIST OF FIGURES</u>	<u>PAGE</u>
Figure 1.1 Transmission spectrum of LPG with and without bending [19]	8
Figure 2.1 Simulated electric field profile of the fundamental guided mode. It can be seen that the electric field extend partially beyond the core-cladding interface	23
Figure 2.2 β -plot showing the propagation constants of both forward and reverse propagating core and cladding modes. $\beta^{(1)}$ is the lowest forward propagating cladding mode [39]	24
Figure 2.3 Perturbation in the core of the fiber can be induced by inscribing a uniform modulation of refractive index	26
Figure 2.4 Pictorial representation of diffraction of a light by a fiber Grating	27
Figure 2.5 A simulation showing the exchange of energy between two modes when (a) phase-matching condition is not met, $\delta \neq 0$ and (b) phase-matching condition is met, $\delta = 0$	30
Figure 2.6 Transmission spectrum of a long period grating with gratings period of $450\mu\text{m}$.	31
Figure 2.7 A graphic representation of fiber Bragg gratings.	32
Figure 2.8 Characteristic curve of FBG showing the relationship between grating period and the reflected Bragg wavelength.	33
Figure 2.9 Mode coupling mechanism in fiber Bragg grating shows that large value of $\Delta\beta$ required small grating periodicity to study the phase-matching condition.	34
Figure 2.10 A common configuration of FBG sensor setup.	35
Figure 2.11 Experimental results of compression test on concrete cylinder with surface mounted FBG sensor.	37
Figure 2.12 Measurement of reflection Bragg wavelength shift with temperature.	38
Figure 2.13 Phase plot of resonant cladding modes for a step index optical fiber. Lower order modes are to the right [50].	41
Figure 2.14 Mode conversion of a fundamental core mode into a forward propagating cladding mode in an optical fiber with long period grating inscribed	41

Figure 2.15 β -plot of mode coupling mechanism in a LPG.	42
Figure 2.16 Near-field intensity distribution of LP_{0m} cladding modes with (a) $m=4$, (b) $m=5$, (c) $m=6$, (d) $m=7$ [52].	43
Figure 2.17 Characteristic curves for the first ten cladding modes in SMF-28 [54]. The dashed curve corresponds to λ_{cut} for different period	47
Figure 2.18 Different wavelength shift of four different resonance dips of a LPG shows different sensitivity for different cladding mode order. The location of the bands A, B, C and D are 1608.6 nm, 1332.9 nm, 1219.7 nm and 1159.6 nm, respectively at 31.2 °C. The dashed line (E) is the shift for a Bragg grating at 1550 nm with a temperature coefficient 1.3 nm/100 °C [64].	57
Figure 2.19 Graph shows the wavelength shift between LPG for different cladding mode (solid line) and FBG (dashed line) under strain. The location of A, B, C, D are 1607.8 nm, 1332.4 nm, 1219.3 nm and 1159.3 nm [54].	59
Figure 2.20 Top graph shows the LPG resonance wavelength response to external index change. Bottom graph shows the effect of external index on the peak loss of the LPG resonance dip [67].	61
Figure 2.21 Experimentally measured core mode transmission losses for several refractive indexes surrounding the LPG.	62
Figure 3.1 Setup configuration of amplitude mask technique for the fabrication of long period gratings.	67
Figure 3.2 Evolution of a typical long period grating using an amplitude mask on UV exposure; curves A to E represent the transmission spectrum in one- minute intervals after the exposure was initiated [40].	68
Figure 3.3 Transmission spectrum of a long period grating with a period of $\Lambda=450\mu\text{m}$. The discrete spiky loss dips corresponds to the coupling of the fundamental core mode to discrete cladding modes.	69
Figure 3.4 Setup for batch fabrication of long period grating just by using a single amplitude mask.	70
Figure 3.5 Schematic layout of the LPG fabrication system using CO_2 laser technique.	72
Figure 3.6 Schematic diagram of optical power distribution on cross-section of a single-mode optical fiber.	73
Figure 3.7 Experimental setup of the LPG fabrication system using infrared femtosecond laser [72].	75

Figure 3.8 Schematic diagram of the experimental setup of electric arc fabrication system for the fabrication of LPG.	77
Figure 3.9 Schematic diagram of a corrugated LPG [74].	79
Figure 3.10 Diagrams show the continual growth of the 450 μm LPG spectrum immediately after UV-laser illumination has stopped. (a) spectrum immediately after the UV-laser is switched off. (b) spectrum after 2 mins. (c) spectrum after 4 mins. (d) spectrum after 6 mins.	82
Figure 3.11 (a) shift of resonance wavelength with time after UV-laser illumination. (b) growth of resonance dip with time after UV-laser illumination.	83
Figure 3.12 The diagram shows a section of the hydrogen-loaded fiber exposed and unexposed the UV-laser illumination during LPG fabrication.	84
Figure 3.13 Shift of LPG resonance wavelengths due to annealing at temperature of 150 $^{\circ}\text{C}$ [40].	87
Fig 3.14 Transmission spectrum of a 320 μm LPG (a) before annealing, (b) after annealing at 100 $^{\circ}\text{C}$ for 20 hrs.	88
Figure 4.1 Non-linear axial strain versus force applied to bare FBG [93].	93
Figure 4.2 Linear axial strain versus force applied to embedded FBG [93].	94
Figure 4.3 Carbon-fiber composite prepeg comes in either unidirectional-reinforcement or fabric-reinforcement [96].	96
Figure 4.4 Simulated longitudinal stress distribution along a rectangular structure.	97
Figure 4.5 Simulated longitudinal stress distribution along a triangular structure.	97
Figure 4.6 A pictorial presentation of fabrication of carbon-fiber composite laminate through multiple layers stacking of composite prepeg.	99
Figure 4.7 Complete preparation setup of the laminate fabrication process before curing.	100
Figure 4.8 Diagram shows a prototype version of the ELPG.	101
Figure 4.9 Experimental setup used for investigation of ELPG spectral response to bending.	101
Figure 4.10 Experimental measurements of the LPG transmission spectrum for different surrounding refractive indexes.	103

Figure 4.11 The diagram shows the spectrum of a 320 μm LPG before embedding.	105
Figure 4.12 The diagram shows the spectrum of a 320 μm embedded LPG before the curing process.	105
Figure 4.13 The diagram shows the spectrum of a 320 μm LPG after curing process.	106
Figure 4.14 Graphical illustration of the cladding mode field distribution shows that the field overlap in the fiber core between the cladding mode and core mode is reduced for curved LPG (b) instead of straight LPG (a).	108
Figure 4.15 Spectral response of ELPG under different bending curvature shows a change in coupling strength.	108
Figure 4.16 Graph plots the absolute value of the ELPG transmission dip with respect to increasing bending curvatures.	112
Figure 4.17 Diagram shows a plot of results obtained from the repeatability test.	114
Figure 4.18 Diagram shows the plot of the results obtained during the hysteresis test.	115
Figure 4.19 Diagram shows the test results of bending on the opposite side of the ELPG.	116
Figure 4.20 Diagram shows that compression occurs at the topside of the laminate while the latter experienced tension at the bottom side.	117
Figure 4.21 Experimental results from bending ELPG embedded at neutral axis of a 6 layers laminate. (a) shows the results by bending on one side of the ELPG while (b) shows the results by bending on the opposite side of the ELPG.	118
Figure 4.23 Figure shows that effect of temperature change on the wavelength and coupling strength of the SMF ELPG bending sensor.	123
Figure 5.1 Optical gain spectrum of erbium-doped fiber amplifier with different pump power.	129
Figure 5.2 Experimental setup of EDFA with ELPG for dynamic gain equalization.	132
Figure 5.3 Experimental results show that the ELPG resonance dip reduces with increased bending while its resonance wavelength remains at 1530nm.	133

Figure 5.4 ELPG characteristic curve which shows the absolute values of the resonance dip with against bending curvatures.	134
Figure 5.5 EDFA transmission spectrum without gain equalization (blue line) and with gain equalization using ELPG (red line).	135
Figure 5.6 Dynamic ELPG compensated EDFA gain spectrum at pump currents of 80 mA, 100 mA and 200 mA.	135
Figure 5.7 Block diagram of an automated ELPG gain equalization system.	136
Figure 6.1 System setup for fabrication LPG.	141
Figure 6.2 LPG high humidity sensor prototype packaged together with a brass tube to prevent bending (Dimensions in cm).	142
Figure 6.3 Experimental setup shows that the gelatin-coated LPG was placed in the climate control chamber during test.	143
Figure 6.4 The resonance wavelength in the transmission spectrum of a bare LPG is located at 1543.186 nm.	144
Figure 6.5 Comparing with Figure 6.4, the resonance wavelength had shifted 6.486nm towards the shorter wavelength or blue shift after the gelatin was applied and dehydrated.	145
Figure 6.6 Figure shows the wavelength shift of the LPG with respect to refractive index of external medium.	147
Figure 6.7 Figure shows the coupling strength changes of the LPG with different external refractive index.	147
Figure 6.8. Shift of resonance wavelength caused by coupling between core mode and the LP_{07} and LP_{08} cladding modes as a function of the overlay thickness [113].	148
Figure 6.9 Graph shows the spectrum response of the gelatin-coated LPG when subjected to different values of relative humidity.	149
Figure 6.10 Response curve of gelatin-coated LPG shows that the latter is highly sensitive at RH beyond 90 %RH.	152
Figure 6.11 Figure shows the response of the gelatin-coated LPG RH sensor to region of high humidity.	153
Figure 6.12 Figure shows the response curve of the PVA-coated LPG RH sensor.	155

Figure 6.13 Repeatability test shows that the response of the gelatin-coated LPG RH is highly repeatable.	155
Figure 6.14 Figure shows the results from hysteresis test.	156
Figure 6.15 Stability test of the gelatin-coated LPG RH sensor produced a stability error of ± 0.05 %RH, under a constant humidity of 95 %RH and temperature of 25 °C.	157
Figure 6.16 Results show that as gelatin concentration increases the sensor sensitivity decreases.	158
Figure 6.17 Pictorial illustration of the penetration depth of water vapor into gelatin layer for different gelatin concentration.	159
Figure 6.18 Graph shows the sensitivity of the gelatin-coated LPG sensor to RH for different cladding mode order.	160
Figure 6.19 The graph shows that change in temperature causes changes in output of the gelatin-coated LPG RH sensor.	162
Figure 6.20 Test results show small reduction of coupling strength of a bare LPG with temperature.	163
Figure 6.21 A comparison plot shows sensor response after fabrication and 3 months later.	164

<u>LIST OF TABLES</u>	<u>PAGES</u>
Table 1.1. Review of LPG-based bending sensor.	17
Table 1.2. Review of optical fiber-based humidity sensor.	18
Table 2.1. Sellmeier parameters for bulk glass samples of different composition [46].	46
Table 4.1. Measured and calculated resonance dip power of embedded H ₂ -loaded ELPG bending sensor, when the temperature is maintained constant.	124
Table 4.2. Measured and calculated resonance dip power of embedded H ₂ -loaded LPG bending sensor, when the bend curvature is maintained constant.	125
Table 4.3. A comparisons of calculated curvature against experimentally measured. Results from both fiber types show similar percentage error.	126

List of Acronyms

CFCM	Carbon-fiber composite material
DAQ	Data acquisition
DWDM	Dense wavelength division multiplexing
ELPG	Embedded long period grating
EMI	Electromagnetic Interference
EDFA	Erbium-doped fiber amplifier
ESG	Electrical strain gauge
FBG	Fiber Bragg grating
GODC	Germanium-oxygen deficiency centers
LED	Light emitting diode
LPG	Long period grating
MI	Matrix Inversion
MLP	Multiplayer perceptron
OSA	Optical spectrum analyzer
POF	Plastic optical fibers
PVA	Polyvinyl alcohol
RI	Refractive index
RH	Relative humidity
SLED	Super luminescence emitting diode
SMF	Single-mode fiber
TLS	Tunable laser source
UV	Ultra-violet

CHAPTER 1: Introduction

1.1

INTRODUCTION

In any decision making process, information has to be captured and evaluated. This process has been going on since the beginning of time and even so in the future. Information to be captured or sensed can come from many areas such as civil engineering, biomedicine, aerospace, environment, etc. Currently, electrical-based sensors have been the main component used in sensing. Despite their popularity, the electrical sensors suffer from numerous drawbacks such as sensitivity to electromagnetic interference (EMI) and lack of multiplexing capability. To shield the sensor from EMI, the normal copper electrical cables have to be replaced with special shielded cables. These problems however can be overcome through the adaptation of optical fiber sensors. Owing to the well known advantages of optical fiber, such as immunity to electromagnetic interference, lightweight, small size, large bandwidth and passive [1], optical fiber sensors have been used as a complement to the electrical counterparts. Being intrinsically safe, applications of optical fiber sensors go beyond places, where using the electrical counterparts were deemed too risky, such as oil refineries and chemical processing plants.

The quest for more cost effective and efficient telecommunications devices has brought about greater research efforts in increasing the reliability of optical devices and thus lowering the cost. Technology developed for one industry also benefits another area. Optical fiber sensors now enjoy the advantages of these advances and hence have gained attention and are being used frequently to substitute conventional electrical ones in environments where the latter cannot be used. Despite these advantages, implementation of optical fiber sensors in industries does come with a few

concerns such as cost, fragility, reliability and complexity. Companies might be too conservative to accept new a technology knowing that it might be facing issues such as reliability and accuracy during this initial phase.

Numerous optical fiber-based sensors have been developed in which the properties of the propagating light are altered and correlated to an externally-induced physical or chemical parameter. The properties of the propagating light to be studied include intensity, phase, wavelength (color), polarization state, and time-of-flight. Two most commonly implemented optical fiber sensors for strain, pressure and temperature measurements are the Fabry-Perot optical fiber sensors and fiber grating-based sensors. A Fabry-Perot optical fiber sensor uses the concept of Fabry-Perot interferometer, in which interference occurs at the partially reflecting end face of an optical fiber and an external mirror [2]. Fabry-Perot optical fiber sensors offers high sensing sensitivity but are only a single point sensor which means they cannot be multiplexed to form multiple sensors network. In addition, to achieve good interference signal, precision alignment between the fiber and the external mirror is critical. Fiber grating-based sensors operate based on the changes on the uniform gratings that are inscribed in the optical fiber core and hence there is no need for precise alignment. In addition, multiple grating-based sensors can be multiplexed on a single strand of fiber, which is an advantage if sensor network has to be implemented [3].

There are two main types of grating-based optical fiber sensors, namely short-period or Bragg gratings and transmission-based or long period gratings. Fiber Bragg gratings (FBG) sensors operate on changing the optical properties of the back-

reflection of light within the core of the fiber, which results in the change of the back-reflected wavelength. FBG sensors have been implemented for various types of perturbation monitoring such as strain, temperature [4, 5, 6] and chemical [7, 8, 9]. The principle of a long period grating (LPG) sensor is based on the change of the optical property of the forward propagating cladding modes. An LPG consists of a uniform modulation of the refractive index, with grating periods between $100\mu\text{m}$ and $1000\mu\text{m}$, within the optical fiber core. This modulation of refractive index results in the coupling of fundamental forward propagating core mode into discrete forward propagating cladding modes, in which the latter is sensitive to external perturbations.

The advantages of LPGs over FBGs include the elimination of back reflection as the cladding modes in the LPG are propagating in the forward direction. Back-reflection will induce source oscillation which will in turn affect the output of the sensor. To solve this problem, an optical isolator will be required to prevent this back-reflection. Fabricating an LPG requires less costly metallic amplitude mask as compared to using very expensive quartz phase mask for fabricating an FBG. This helps to reduce the overall cost in implementing sensor system. Another attractive feature of using an LPG is in the area of chemical or refractive index sensing. Using an FBG for chemical or refractive index sensing can be very complex as it requires the etching of the cladding to within a few microns from the core to gain access to the evanescent field of the guided mode [10, 11]. This etching process will reduce the strength and integrity of the sensor and degrades the sensor's performance under harsh working environment conditions. On the other hand, no etching is required when using LPG for refractive index sensing, as the external medium can interact with the cladding mode at the cladding/air interface. Hence structural integrity of the fiber is

being preserved. Having these advantages, using LPG as a fiber sensor has attracted much interest over the years.

There have been numerous works relating to the use of LPG as fiber sensors that have been published. The range of sensing applications spread from temperature, strain, bending sensing, measurement of refractive index of solutions, to specialized sensing applications such as chemical, biomedical and environmental. The popular applications using LPG sensor are the bending sensing and environmental sensing. Bending sensing is important in monitoring structures such as bridges and skyscrapers. A review on the LPG bending sensors, which will be presented later, shows that all the results from the LPG bending sensors are wavelength-based data. What it means is that the LPG bending sensors convert the bending curvature into resonance wavelength shift in its spectrum. Demodulation of the wavelength-based data requires complex and expensive wavelength interrogation system and will thus increase the complexity and cost of a sensor system. If the LPG fiber sensor converts the perturbation of interest into intensity-based data, demodulation of these data will be simpler and less costly, since detection can be done using a simple photodetector system. This will thus bring down the overall cost of implementing the fiber sensor system.

Under environmental sensing application, humidity sensing is an important application. Humidity is critical in various areas such as industrial process control in semiconductor processing [12], pharmaceutical facilities [13], and geotechnical monitoring [14]. In industrial process control such as semiconductor or pharmaceutical manufacturing, precise control of humidity conditions is necessary for reliable

manufactured products. In geotechnical measurements, high humidity sensing plays a very important role in determining the stress state and moisture content in soil. From a thermodynamic point of view, the relative humidity of a soil represents the state of energy of the water present in the soil, which in turn determines the stress state in the soil. The stress state in the soil determines the shear strength, volume change and hydraulic behaviour of the soil [14]. Typical values of high RH in soils range from 90 %RH to 100 %RH, but majority of soils have humidity of 99 %RH and above. Relative humidity sensors include electrical types using physical quantities that vary with humidity like electrical resistance, capacitance, thermal conductivity or wet-dry bulb methods [15]. Most humidity sensors have difficulty measuring high RH due to condensation of water from the atmosphere onto the sensing region [16]. Condensation can cause the electrical sensors to short circuit or produce readings that are not repeatable or erratic. In addition, electrical based humidity sensors are prone to electromagnetic interference (EMI) that will affect the readings. The long-term stability of the sensors is also a problem due to the lifetime of the sensor, which is susceptible to corrosion in high humidity environments. Remote sensing using electrical sensors is problematic too, as long-distance monitoring will require a long length of cables, which can be very heavy and expensive. Long electrical cables also generate electrical noise that may further distort the data. Having a RH sensor that measures high RH in the range of 90 %RH to 100 %RH, with additional properties of the sensor being simple, reliable, repeatable, easy to install and demodulate, will be very desirable in situations where high humidity monitoring is a necessity.

From our work, two novel intensity-based LPG sensors were developed and characterized. The first sensor was the embedded LPG (ELPG) bending sensor in

which the ELPG's resonance dip changes with bending curvatures while its resonance wavelength remains unchanged. The second sensor was the gelatin-coated LPG high relative humidity sensor in which its resonance dip changes with variations in high RH while its resonance wavelength remains relatively constant. Both LPG sensors are targeted to provide solutions to industrial problems. It has been known that intensity-based sensors systems suffers from problems associated with the intensity fluctuation of the light source. However if these fluctuations are small with respect to the changes induced by the measurand, and the fluctuation in the sensor's output due to the changes in the intensity of the light source can be neglected. There is therefore a compromise between cost and accuracy. Depending on the requirements, if the intensity-based fiber sensor system is able to fulfill these requirements and there is no added advantage in using the wavelength-based fiber sensor system, it will be more appealing for companies to invest in a simpler and more economic intensity-based fiber sensor system.

Like any other system, a wavelength-based fiber sensor suffers from cross-sensitivity. One good example is the case of using FBG sensor as strain sensor. Not only is the FBG sensitive to strain, it is also sensitive to temperature. This problem can however be resolved by using another FBG sensor, that is not subjected to strain, as a reference. This helps to increase the accuracy of the readings. Likewise, light source power fluctuation can also be compensated by using a reference arm and a ratio detector. In addition, with improved fabrication technology and better circuit design, the newer generation light sources are expected to be more stable. A review of the current work and a summary of the two new intensity-based LPG sensors will be given below in two separate sub-sections.

a) Review of fiber sensor for bending sensing

An embedded LPG (ELPG) is formed by embedding an LPG in between layers of carbon-composite laminates. This embedding provides ruggedness and protection to the optical fiber that allows the ELPG bending sensor to be applied in areas such as in the offshore Jackup drill rigs which is designed to carry out operations under harsh environmental conditions. A review of previous works published shows that most of the LPG bending sensors are wavelength-modulated based sensors. The first work on the use of LPG as a bending sensor was published by H. J. Patrick and co-workers in 1998 [17]. Study shows that bending of the LPG results in a red shift of LPG resonance wavelength. Theoretical analysis showed that the spectral shift of the resonance wavelength is due to the change in the period of the gratings and the strain caused in the core of the optical fiber [18]. Despite non-linear output response, the sensor yields a total wavelength shift of 16 nm for a bending curvature of 4.4m^{-1} . This gives the sensor a bending sensitivity of 3.6 nm/m^{-1} . In another method, Y. Liu and co-workers demonstrated that bending of an LPG yields splitting of the resonance wavelength or cladding mode into two separate cladding modes as show in fig. 1.1 [19]. As the bending curvature increases, the higher resonance wavelength, of the split wavelength, will induce greater red shift and vice versa for the lower resonance wavelength. Therefore the distance between the two resonance wavelengths indicates bend curvature. At a sensitivity of 14 nm/m^{-1} , this sensor is more sensitive than the one in ref. [17]. However, both sensors above measure only a single bending direction.

Fig. 1.1 Transmission spectrum of LPG with and without bending [19].

Donghui Zhao and co-workers demonstrated an LPG bending sensor that is able to recognize bending direction [20]. In this work, the authors inscribed the LPG into an elliptical core fiber which has a flat cladding surface parallel to the major axis of the ellipse. This type of fiber is also named as D-shaped fiber and the name for the LPG written in this fiber is DLPG. As the elliptical core is located off the neutral axis of the D-shaped fiber, the elliptical core will experience compression or expansion strain when bended, depending on the bending direction with respect to the flat cladding surface. The strain will then be translated by the LPG into wavelength shift with the direction of shift depending on whether if the LPG is experiencing compression and expansion strain. Although a single D-shaped fiber is able to handle directional bend measurement, handling of the D-shaped fiber is not easy as the fiber has an overall diameter which is half of that of a single mode fiber. This means that the fiber is very fragile and cost of each fiber is high due to the difficulty in fabricating it. In addition, splicing the D-shaped fiber to a standard single mode fiber may pose a

problem. This is due to the geometric difference between the D-shaped fiber and standard single mode fiber.

These shortcomings can however be overcome using LPG where the fiber cladding refractive index is asymmetrically modified. Using a standard single mode fiber with LPG inscribed in the core, T. Allsop and co-workers induced an asymmetric refractive index change in the fiber cladding using a femtosecond laser [21]. Bending on the LPG sensor will induce either a blue shift or red shift of the LPG resonance wavelength, depending on the bending direction with respect to the direction of the femtosecond laser incident on the fiber. Using this method, the structural integrity of the fiber has been preserved.

Although most development of LPG bending sensors resulted in wavelength-based sensor, interrogating them would require the use of expensive and complicated wavelength interrogation system such as optical spectrum analyzer as mentioned earlier. In addition, the combined effect of strain and temperature induced on the sensor can have an impact on the outcome of the data collected. To compensate for the cross-sensitivity, an additional LPG free from bending, has to be used to reduce the cross-sensitivity effect. A method proposed by S. Chen et al. uses LPG that is fabricated on a special temperature- and strain- insensitive fiber [22]. By using the temperature- and strain- insensitive fiber, the cross-sensitivity effect from both temperature and strain is reduced but it comes with a cost due to higher price of this special type of fiber used.

Instead of using wavelength-based LPG sensor to measure bending, the same measurand can also be measured using intensity-based LPG. Advantages of using this method include the use of a cheap and less complex intensity interrogation system, such as a photodetector, and a reduction of the cross-sensitivity effect with temperature. There are publications which reported the measurement of bending by monitoring the misalignment between two facing optical fiber due to bending [23] and the use of etched fiber Bragg gratings [24]. However both methods have problems such as difficulty in aligning the two optical fiber ends [23], especially for single mode fiber and the weakening of fiber structure due to etching [24]. At the present, not much work has been reported on intensity-based LPG bending sensor. This could be due to the difficulty of obtaining an LPG sensor which changes only its resonance dip while maintaining resonance at the same wavelength.

Y. J. Rao and co-workers exploited the use of heat to fix the LPG resonance wavelength location while the resonance dip changes when the LPG undergoes bending [25]. This method requires extra calibration of the heating element so that the wavelength shift induced by bending matches that to the reverse wavelength shift induced by heat. G. D. VanWiggeren and co-workers had demonstrated another method such that a bending with respect to the correct fiber axial orientation of a CO₂-induced LPG causes the LPG resonance dip at the fixed resonance wavelength to change [26]. When an optical fiber is exposed to the CO₂ laser, due to the absorption of the radiation by the optical fiber, the side of the optical fiber facing the CO₂ laser directly will be most affected, with the radiation decaying exponentially away from the surface. The index change is therefore highest at the front region of the optical fiber. As the induced refractive index across the cross-section of the optical fiber is not even,

the region where the bending force is orthogonal to may not have highest refractive index change. Therefore this may result in wavelength shift instead of intensity change. The report shows that the CO₂-induced LPG bending sensor is able to measure only one bending direction. The use of extra equipment, extra steps and fiber orientation dependence can be troublesome at times.

In this research work, a novel intensity-based LPG bending sensor embedded in carbon-fiber composite material has been developed where bending causes changes only in the ELPG resonance dip and not in the wavelength, thus making possible the use of cheap photodetector instead of the expensive wavelength interrogation system. In addition, embedding the LPG in carbon-fiber composite material enhances the sensor's ruggedness and durability, thus allowing the ELPG to withstand harsh environments conditions. As the LPG is fabricated using a UV laser, the bending direction is independent of fiber axial orientation. This is due to the uniform optical fiber cross-sectional refractive index profile of the grating inscribed. Handling difficulty issue has thus been reduced. Further investigations of the ELPG has shown that ELPG can also be used to measure bending direction, which has not been demonstrated for any intensity-based LPG reviewed above. An explanation of the phenomenon and characterization of the ELPG will be presented later in the chapter 4.

b) Review of fiber sensor for humidity sensing

Relative humidity (RH) is the ratio of the actual partial vapor pressure of water to the saturation vapor pressure at that temperature, and is expressed in percentage. Most research works on optical fiber based-humidity sensor use plastic clad silica (PCS) optical fiber or plastic optical fiber (POF). K. Ogawa and co-workers developed

an optical fiber humidity sensor using a PCS fiber, having a section of the cladding region etched away and replaced with microporous SiO_2 , which has refractive index that is lower than that of the PCS fiber core [27]. As humidity increases, the refractive index of the microporous SiO_2 increases and approaches that of the core. As a result light “leaked” from the fiber core into the absorptive microporous SiO_2 cladding region. Therefore the optical power output from the fiber varies according to amount of moisture absorbed by the microporous SiO_2 cladding, which is in turn dependent on humidity of the surrounding.

Another method of optical fiber-based humidity sensing involved bending of the POF or PCS fiber and coating the unclad bent region with light absorptive coating, which is sensitive to humidity of the surrounding. The coating used is Cobalt Chloride (CoCl_2) mixed with polyvinyl alcohol (PVA) [28, 29]. Bending of the fiber will cause more light, propagating in the fiber core, to leak into the coating region, thereby increasing the sensor’s sensitivity. The purpose of PVA in the CoCl_2 /PVA coating is to hold CoCl_2 while the latter is used as a colorimetric reagent to detect the presence of humidity. CoCl_2 strongly absorbs 690nm light when dry. At low humidity, the optical power output from the fiber is less due to the absorption of light by CoCl_2 . By comparison, the absorption capability of CoCl_2 , at higher humidity, reduces leading to higher optical power throughput. Humidity sensing using bent PCS coated with CoCl_2 /PVA overlay had been demonstrated to measure humidity ranging between 10 %RH and 90 %RH [28]. Other type of large core fibers such as POF has been used for humidity sensing [30, 31]. This allows cost reduction as the cost of POF is lower than PCS fiber.

Despite the advantage of the large core diameter of PCS fiber and POF (200 μm to 600 μm for PCS fiber and 0.5 mm to 2 mm for POF) for coupling more light into the fiber, PCS fiber and POF have incompatibility issue of not being able to integrate with current optical communication components. Splicing of PCS fiber and POF with standard single mode fiber is not possible due to size mismatch. Instead of using PCS fiber and POF, there had been publications reporting the use of standard single mode fiber (SMF) for humidity sensing.

The work on single mode fiber-based humidity sensor was first demonstrated by D. C. Bowness and co-workers using polyethylene (PEO) as humidity sensitive film coated on bent SMF [32]. Bending the SMF causes light propagating in the fiber core to be coupled out into the cladding, forming whispering gallery (WG) modes due to the cladding/coating interface. Interference pattern is thus formed between the core mode and the WG mode. The interference intensity is dependent on the strength of the WG mode which is determined by the refractive index of the overlay coating. At low humidity, the overlay PEO coating refractive index is higher than that of the cladding and there exists only a weak Fresnel reflection of the WG mode at the cladding/coating interface. Therefore no interference occurs. At higher humidity, the PEO refractive index falls below that of the cladding and total internal reflection of the WG mode occurs. This results in strong interference oscillation pattern observed by the authors [33]. There is however a disadvantage pertaining to this method. Reproduction of the sensor with identical spectral characteristics is very difficult which is due to the nature of the WG interference rather than the overlay material itself.

Another technique of measuring humidity using SMF is to tap into the evanescent wavelength of the light propagating in the fiber. To gain access to the evanescent wave means that the cladding region has to be etched down to a few hundreds of nm from the fiber core. A. Geston and co-workers [33] had developed a humidity sensor using side-polished SMF coated with PVA and measured a humidity range between 70 %RH and 90 %RH. The sensor operates based on the interaction between PVA and the evanescent wave. At low humidity, the PVA has a refractive index higher than that of cladding thus allowing the evanescent wave to propagate through the lossy PVA coating region. At higher humidity, due to a decrease in PVA refractive index, the degree of evanescent wave penetrating into the PVA region will be reduced, resulting in a higher optical power throughput. Etching of fiber although allows access to the evanescent wave, it does so at the expense of a weakened fiber structure. Etching the fiber will increase the handling difficulty of the fiber, thus increasing the cost of the sensor as a whole.

This shortcoming can be overcome by coupling the light into the cladding region so that the evanescent wave can be accessed through the cladding/air interface. This can be done with a long period grating or LPG. A LPG couples light from the core mode into cladding modes. Hence with the cladding modes propagating along the fiber cladding region, access to the evanescent wave is made possible without the need to etch the fiber. At this point of the review, only one work has been done using LPG for humidity sensing [34]. S. Luo and co-workers used carboxymethylcellulose (CMC), which is humidity sensitive, and applied an overlay coating on the LPG. The authors observed a shifting of the LPG resonance wavelength with humidity. This is due to the changes of the CMC refractive index which is lower than that of fiber

cladding, with humidity and thus affecting the LPG's phase matching condition. The CMC-coated LPG humidity sensor measures humidity up to 95 %RH. Beyond 95 %RH, the sensor output becomes unstable as the CMC coating approached fully saturated stage. The sensor, being wavelength-based, will be subjected to cross-sensitivity effects from strain and temperature which affects the resonance wavelength location. Moreover as mentioned earlier, more expensive and complicated wavelength interrogation system is required to interrogate the sensor, adding cost to the overall sensor system.

By far most works on RH sensing mentioned above developed exploit the humidity sensitive polymer coating's light absorption capability and refractive index change as a means for RH measurement. A Maclean *et al.* made use of the swelling of the hydrogel polymer for RH sensing [38]. In this work, the authors used a swellable hydrogel polymer to induce microbend loss on the optical fiber which can be interrogated using a standard Optical Time Domain Reflectometry (OTDR) instrument. Experimental results showed that their setup exhibits a significant response at relative humidity above 90%. However the result did not show a linear response. In our experiments, we discovered that gelatin-coated LPG exhibits high sensitivity to changes in high RH in the range between 90 %RH and 99 %RH. The response of the gelatin-coated LPG RH sensor exhibits a linear relationship with RH. The new gelatin-coated LPG high RH sensor overcomes the shortcomings, in wavelength-based sensor, by having the results intensity-based. The new LPG humidity sensor works on the interaction between the thin gelatin-coating and the LPG's cladding mode, where the latter's effective refractive index is close to that of cladding. The LPG resonance dip changes its coupling strength with varying RH. As the LPG is fabricated on the

standard telecommunication optical fiber, the sensor can be easily integrated with existing communication systems unlike other RH measurement methods using POF based RH sensor. The reason is that the LPG can integrate with any optical fiber communication network, for humidity monitoring, without the fear of power coupling issue and incompatibility. In addition, the LPG can use light source in the communication system. RH measurement using LPG has another advantage over conventional optical fiber-based RH measurement methods in that etching of cladding is not required for LPG. Hence structural integrity of the optical fiber is not affected.

A summary of work published on LPG bending and humidity sensors can be found in table 1.1 and table 1.2 respectively.

Review of LPG-based bending sensor		
Year	Title	Type of modulation
2001	Tuning, attenuating and switching by controlled flexure of LPFG [26]	• Intensity-based
2004	Intensity-based Fiber optical bending sensor for potential railway applications [23]	• Intensity-based
2004	Bend sensor using an embedded etched fiber bragg grating [24]	• Intensity-based
2005	A novel dynamic LPFG gain equalizer written in a bend-insensitive fiber [35]	• Intensity-based
1998	Long period fibre gratings for structural bend sensing [17]	• Wavelength-based
2000	Optical bend sensor based on measurement of resonance mode splitting of long-period fiber grating [19]	• Wavelength-based
2003	Novel long-period fiber gratings written by high-frequency CO ₂ laser pulses and applications in optical fiber communication [25]	• Wavelength-based
2004	Bend sensors with direction recognition based on long-period gratings written D-shaped fiber [20]	• Wavelength-based
2004	A smart bending sensor with a novel temperature- and strain-insensitive long-period grating [22]	• Wavelength-based
2005	Long period grating directional bend sensor based on asymmetric index modification of cladding [21]	• Wavelength-based

Table 1.1. Review of LPG-based bending sensor.

Review of the optical fiber-based relative humidity sensor			
Year	Title	Fiber configurations	Type of modulation
1988	Humidity-sensing effects of optical fibers with microporous SiO ₂ cladding [27]	PCS fiber with cladding removed and replaced with microporous SiO ₂ as cladding.	• Intensity-based
1998	Detection of high humidity optical fiber sensing at telecommunications wavelengths [32]	Bent standard single-mode fiber coated with gelatin or polyethylene oxide (PEO)	• Intensity-based
1998	Hydrogel/Fibre Optic Sensor for Distributed Measurement of Humidity and pH Value [38]	Uses swellable hydrogel polymer to induce microbend loss on optical fiber	• Intensity-based
2001	A novel probe for a fiber optic humidity sensor [36]	Bent PCS fiber coated with phenol red	• Intensity-based
2002	High dynamic range fiber optic relative humidity sensor [29]	Bent PCS fiber coated with with PVA/ CoCL ₂	• Intensity-based

2002	Relative humidity sensor with optical fiber Bragg gratings [37]	Fiber Bragg Gratings on single mode fiber and coated with Pyralin	<ul style="list-style-type: none"> • Intensity-based
2002	Applications of LPG fiber optical sensors for relative humidity and chemical warfare agents monitoring [34]	LPG coated with carboxymethylcellulose (CMC)	<ul style="list-style-type: none"> • Wavelength-based
2003	Evanescent Wave Optical-Fiber Sensing (Temperature, Relative Humidity, and pH Sensors) [33]	Side-polished single mode fiber coated with PVA	<ul style="list-style-type: none"> • Intensity-based
2003	A plastic optical fiber sensor for real-time humidity monitoring [31]	Straight plastic optical fiber coated with an overlay of a mixture of hydroxyethylcellulose (HEC) and polyvinylidene fluoride (PVDF) as cladding	<ul style="list-style-type: none"> • Intensity-based
2004	Humidity sensing using plastic optical fibers [30]	Bent plastic optical fiber coated with PVA and CoCl_2	<ul style="list-style-type: none"> • Intensity-based
2005	An evanescent-wave optical fiber relative humidity sensor with enhanced sensitivity [28]	Bent PCS fiber coated with PVA/ CoCl_2	<ul style="list-style-type: none"> • Intensity-based

Table 1.2. Review of optical fiber-based humidity sensor.

1.2 RESEARCH OBJECTIVES AND CONTRIBUTIONS

LPG-based sensors have many advantages over conventional electrical-based sensors such as immunity to electromagnetic interference and multiplexing capability and etc. Like an FBG sensor, the measurand is also translated into wavelength changes in an LPG sensor. Interrogating wavelength information is expensive due to the need of costly interrogation systems. If the LPG sensor is intensity-based, the cost and complexity at the interrogation end of the whole sensor system can be greatly reduced as simpler and less costly photodetectors are used. This forms the objectives of this research study. From this research, it was found that the LPG sensor optical output can be modified such that changes in measurand can result in intensity changes rather than wavelength changes. This is due to the unique response of LPG optical spectrum to the refractive indices of external medium surrounding the LPG in an optical fiber.

Two novel intensity-based LPG sensors have been developed and characterized. These LPG sensors developed are embedded LPG bending sensor and gelatin-coated high relative humidity LPG sensor. The experimental studies show how an LPG sensor can be converted from a wavelength-based sensor to an intensity-based sensor by the external medium's refractive indices surrounding the LPG. The investigations into this change provide a better understanding of the effect of LPG optical response to the external surrounding medium of refractive index that is close to that of the cladding and the refractive index higher than that of cladding, which will be useful for possible future design of an LPG biosensor and chemical sensor.

Characterizations of both the LPG sensors show good system performance such as linear response, good repeatability and low hysteresis, which is important for industrial applications under harsh environments.

1.3

DISSERTATION OUTLINE

This section gives an outline of the content of this thesis. Chapter 2 outlines the fundamental concept of mode coupling between the two modes propagating in the optical fiber. For maximum power transfer between the two modes, phase-matching condition must be met. This chapter also presents an overview of the short period grating or the fiber Bragg grating, in which the forward propagating fundamental core mode, upon satisfying the phase-matching condition is coupled to a backward propagating core mode. In the portion on long period grating, the area of coverage includes the fundamental concept, characteristic curves and coupling coefficient. A brief introduction to the sensitivity of the long period grating's spectrum to external

perturbation such as strain, temperature and refractive index will also be covered in this chapter.

Long period gratings are made up of uniform modulation of refractive index in the core of an optical fiber. A common technique for the fabrication of gratings is through ultra-violet laser radiation on photosensitive optical fiber using the amplitude mask technique. Although amplitude mask technique is a commonly used technique, there are also other techniques suitable for fabricating long period gratings and these techniques will be covered in chapter 3.

Unlike fiber Bragg grating fabrication process, the process of fabricating LPG is not as easy. This is due to the instability of the LPG transmission spectrum at the end of the UV exposure when using hydrogen-loaded optical fiber. In chapter 3, an insight into the stability of the LPG transmission spectrum immediately after UV exposure will be presented. The purpose is to share with any reader, who will be writing LPG, on the problems commonly faced when writing LPG using hydrogen-loaded optical fiber.

Chapter 4 will focus on the experimental results and discussions on the novel embedded LPG (ELPG) bending sensor. It was found that the ELPG bending sensor exhibits a different phenomenon as compared to other types of LPG-based bending sensor, where the ELPG resonance dip changes its amplitude rather than wavelength with bending. An explanation was proposed to explain this phenomenon. A full characterization on the sensor was carried out and the results will be presented in this chapter. Although the original intention of using an ELPG is for bend sensing, this

new technique has also been demonstrated to be useful for dynamic equalization of an Erbium-doped fiber amplifier's gain spectrum. The results of this work will be discussed in chapter 5.

Chapter 6 will focus on the gelatin-coated LPG high relative humidity sensor. Like the ELPG bending sensor, the resonance dip of the gelatin-coated LPG changes its depth at different humidity. An explanation to this phenomenon is also proposed in this chapter. Finally, results from full characterization of this sensor, including sensitivity, repeatability, hysteresis, stability, etc, will also be discussed.

The last portion of this thesis is a summary of the research work done along with recommendations for future work which encompasses the theoretical work on the embedded LPG bending sensors, temperature compensation for the LPG humidity sensor and overcoming technical issues associated with the LPG humidity sensor.

CHAPTER 2: Fundamentals of Long Period Gratings

In this chapter, the concept of coupling or exchange of power between the fundamental guided core mode into another mode will be discussed. This is the fundamental principle that governs the operation of fiber Bragg grating and long period grating.

2.1

INTRODUCTION

In a perfect optical fiber, in which the refractive index and physical dimension are homogenous along the fiber axis, a fundamental guided core mode will remain propagating in the core along the fiber axis. Due to manufacturing process, which causes fiber waveguide imperfection, perturbation exists in the fiber system and this causes coupling between the fundamental mode into other modes such as radiation modes. Another means of introducing perturbation into the core will be by the introduction of periodic refractive index modulation in the fiber core. Two such optical devices with uniform periodic modulation of refractive index induced into the optical fiber core are fiber Bragg gratings and long period gratings. Both gratings have attracted attention from researchers into the use of it in sensing application. However, with the additional capacity for measuring refractive index of external medium and potential in biomedical sensing, long period grating (LPG) has attracted an even greater attention.

Before presenting the application of LPG as a sensor, an overview of the mode coupling will be discussed, as this gives a clearer understanding on the concept of long period grating. Although LPG is the focus of the work, an overview on the concept of fiber Bragg grating (FBG) will also be discussed. This is to provide a more complete picture of the two basic types of gratings and allows the reader to appreciate the long

period grating as a sensor. Various characterizations of the LPG properties will be included in this chapter. They are the characteristic curves, the differential propagation constant, coupling coefficient and the modal overlap between the fundamental guided mode and the cladding modes over the region of perturbation.

2.2 MODE COUPLING IN OPTICAL FIBERS

The propagation of light along an optical fiber can be described in terms of a set of guided electromagnetic waves commonly referred to as ‘modes’ of the optical fiber waveguide. Each guided mode is a pattern of electric and magnetic field distributions that is repeated along the fiber at equal intervals. A fundamental guide mode propagating along an optical fiber has its field tightly confined to the core. Although the fundamental mode is concentrated in the core, the electric field of this mode does not go to zero at the core-cladding interface as shown in figure 2.1. Instead, they extend partially into the cladding.

Figure 2.1 Simulated intensity profile of the fundamental guided mode. It can be seen that the intensity profile extends partially beyond the core-cladding interface.

For a monochromatic light with radiation frequency, ω , a mode travelling in the direction z along the fiber has a time and z dependency given by [39];

$$e^{j(\omega t - \beta z)} \quad (2.1)$$

The factor β is the z component of the wave propagation constant in the medium given by $\beta = nk$, where k is the propagation constant in vacuum and n is the refractive index of the medium. For guided modes to propagate in the core of the fiber, there is a range of discrete values of propagation constants, β , over which the modes will be guided and confined to $n_2 k < |\beta| < n_1 k$, where n_1 and n_2 are the core and cladding refractive index respectively.

A convenient graphical representation for describing β for both forward and backward propagated guided and radiation modes can be represented by the β -plot [40], shown in figure 2.2. The propagation constant, β , is rewritten as $\beta = \frac{\omega n}{c}$, where n is the effective refractive index of the medium through which the mode propagates, and $n_2 < n < n_1$.

Figure 2.2 β -plot showing the propagation constants of both forward and reverse propagating core and cladding modes. $\beta^{(1)}$ is the lowest forward propagating cladding mode [40].

Besides supporting the fundamental core mode, the optical fiber can also support an infinite continuum of radiation modes that are not trapped in the core but are still guided by the fiber. These radiation modes are due to the optical power that is outside the fiber's acceptance angle which are refracted out of the core.

Due to the finite radius of the cladding, some of these radiation modes are trapped in the cladding, thereby causing the cladding modes to appear. As with the guided core mode, the electric fields of the cladding modes are not confined completely within the cladding but extend partially into both the cladding-core interface and the cladding-external surrounding interface. Therefore, as the core and cladding modes propagate along the fiber, they get coupled to one another. An exchange of energy between the core and the cladding modes results in the loss of power from the core mode. The coupling of energy from the fundamental guided mode to discrete cladding modes forms the basic operating mechanism of the LPG.

2.2.1 PHASE MATCHING CONDITION

For two modes to exchange a significant amount of energy in the region of perturbation, a phase matching condition must be fulfilled between the two modes. Coupled mode equations will be used to depict the importance of the phase matching condition in an LPG.

In an LPG, a uniform modulation of refractive index has been inscribed in the optical fiber core, as shown in figure 2.3. This modulation of refractive index creates a perturbation to the core mode propagating in the fiber core.

Figure 2.3 Perturbation in the core of the fiber can be induced by inscribing a uniform modulation of refractive index.

A fiber grating is an optical diffraction grating and thus its effect upon a light wave incident on the grating at an angle θ_1 can be described by the familiar grating equation [41],

$$n_2 \sin \theta_2 = n_1 \sin \theta_1 + m \frac{\lambda}{\Lambda} \quad (2.2)$$

where θ_2 is the angle of the diffracted wave and the integer m determines the diffraction mode as shown in figure 2.4. This equation predicts not only the angle θ_2 ,

wavelength at which the fiber grating most efficiently couples light between the two modes.

Figure 2.4 Pictorial representation of diffraction of a light by a fiber grating.

In describing the exchange of energy between two modes under perturbation, let the two modes be denoted by a_1 and a_2 travelling in the positive direction, z , along the fiber axis, with discrete propagation constants β_1 and β_2 respectively such that [42],

$$a_1(z, t) = A_1(z) e^{j(\omega t - \beta_1 z)} \quad (2.3a)$$

$$a_2(z, t) = A_2(z) e^{j(\omega t - \beta_2 z)} \quad (2.3b)$$

where ω is the angular frequency. $A_1(z)$ and $A_2(z)$ are complex normalized amplitudes that are independent of z in a lossless unperturbed fiber. In the presence of perturbation, the energy between the two modes will exchange such that $A_1(z)$ and $A_2(z)$ are functions of the propagation distance [42].

In the perturbed fiber, the amplitude of $A_1(z)$ and $A_2(z)$ along the z -axis is as follows [42],

$$\frac{dA_1(z)}{dz} = \kappa_{12} A_2(z) e^{-j\Delta z} \quad (2.4a)$$

$$\frac{dA_2(z)}{dz} = \kappa_{21}A_1(z)e^{-j\Delta z} \quad (2.4b)$$

where κ_{12} and κ_{21} are termed the cross-coupling coefficients which indicate the magnitude of coupling between the two modes. This cross-coupling coefficient will be covered in the later part of this chapter. Δ is the phase mismatch between the propagation modes [42] and the difference in their propagation constant in the presence of a perturbation of period Λ .

$$\Delta = \beta_1 - \beta_2 - \frac{2\pi}{\Lambda} \quad (2.5)$$

Δ has a strong dependence on the β_1 and β_2 , as these propagation constants are functions of the optical wavelength. For synchronous transfer of power between the modes, the value of Δ should be minimum and ideally zero. With $\Delta=0$, equation 2.5 can be rearranged and becomes,

$$\beta_1 - \beta_2 = \frac{2\pi}{\Lambda} = \Delta\beta \quad (2.6)$$

where $\Delta\beta$ is the differential propagation constant. Equation 2.6 is commonly termed as the phase-matching condition.

Assuming at $z=0$, $a_1(0)=A$ and $a_2(0)=0$, when mode a_1 interacts with the perturbations, a propagating polarization wave is generated that finally results in mode a_2 [42]. The generated mode a_2 further interacts with the perturbations to alter the energy in mode a_1 . This sustained exchange of power between modes a_1 and a_2 is dependent on the differential propagation constant $\Delta\beta$ and the periodicity of the perturbations. In the case of meeting the phase-matching condition, the power transfer between the two modes is a function of the coupling coefficient. Away from the phase-

matching condition, the magnitude of the interaction between the two modes becomes negligible.

The expressions for the power in the two modes, which can be obtained from the complex modal amplitude, $A_1(z)$ and $A_2(z)$, can be expressed as [42],

$$A_1(z) = A \frac{2\kappa_{12}}{\sqrt{4\kappa^2 + \Delta^2}} e^{j\frac{\Delta z}{2}} \sin\left[\frac{1}{2}(\sqrt{4\kappa^2 + \Delta^2})z\right] \quad (2.7)$$

$$A_2(z) = Ae^{j\frac{\Delta z}{2}} \left\{ \cos\left[\frac{1}{2}(\sqrt{4\kappa^2 + \Delta^2})z\right] - j \frac{\Delta}{\sqrt{4\kappa^2 + \Delta^2}} \sin\left[\frac{1}{2}(\sqrt{4\kappa^2 + \Delta^2})z\right] \right\} \quad (2.8)$$

where κ_{12} is the cross-coupling coefficients from mode a_1 to mode a_2 and $\kappa^2 = |\kappa_{12}|^2$.

The power of the two modes, a_1 and a_2 , can be obtained by,

$$P_1(z) = |A_1(z)|^2 = \frac{P_o \sin^2\left[\kappa z \sqrt{1 + \left(\frac{\delta}{\kappa}\right)^2}\right]}{1 + \left(\frac{\delta}{\kappa}\right)^2} \quad (2.9)$$

$$P_2(z) = |A_2(z)|^2 = P_o \left\{ \frac{\cos^2\left[\kappa z \sqrt{1 + \left(\frac{\delta}{\kappa}\right)^2}\right] + \left(\frac{\delta}{\kappa}\right)^2}{1 + \left(\frac{\delta}{\kappa}\right)^2} \right\} \quad (2.10)$$

where $\delta = \frac{\Delta}{2}$ is termed the detuning parameter and P_o is the incident power $P_o = |A|^2$.

From equations 2.9 and 2.10, the frequency and coupling magnitude are functions of the detuning ratio $\frac{\delta}{\kappa}$. The plot in figure 2.5 depicts the variation in the normalized incident power $P_1(z)$ and $P_2(z)$ as functions of κz for different values of detuning ratio.

Figure 2.5 A simulation showing the exchange of energy between two modes when (a) phase-matching condition is not met, $\delta \neq 0$ and (b) phase-matching condition is met, $\delta = 0$.

Figure 2.5 shows that when the phase-matching condition is satisfied, $\delta = 0$, and the exchange of power between the two modes will be maximum. Anywhere away from phase-matching condition, $\delta \neq 0$, and the magnitude of the exchanged power between the two modes reduces. At the phase-matched condition, equations 2.9 and 2.10 can be reduced to;

$$P_1(z) = P_0 \sin^2(\kappa z) \quad (2.11)$$

$$P_2(z) = P_0 \cos^2(\kappa z) \quad (2.12)$$

The above equations show that the magnitude of coupling is determined by the coupling coefficient, κ , and the length of perturbation, z . Figure 2.5(b) also depicts that for maximum coupling to occur, $\kappa z = \frac{m\pi}{2}$, where m is an integer. To obtain the coupling strength or ratio of power between two modes, equation 2.11 can be rewritten as follows:

$$C = \frac{P_1(z)}{P_0} = \sin^2(\kappa z) \quad (2.13)$$

$$C = \frac{P_i(z)}{P_o} = \sin^2(\kappa z) \tag{2.13}$$

Although the coupling coefficient κ will be discussed in the later section, as a whole the coupling strength equation, equation 2.13, is one important component that determines the depth of the resonance dip in the LPG transmission spectrum, as shown in figure 2.6.

Figure 2.6 Transmission spectrum of a long period grating with gratings period of 450μm.

In summary, a coupling of power between two forward propagating modes has been discussed. For maximum degree of exchange of power between two modes, the phase-matching condition has to be satisfied. When phase-matched, the power variation for the modes follows a sinusoidal trend along the direction of perturbation. This condition is the primary condition that governs the principle of operation of FBG and LPG.

2.3 FIBER BRAGG GRATINGS

Fiber gratings can be classified into short or Bragg reflection gratings, or long period transmission gratings. Although the main work of this dissertation is on long

period gratings, for completeness and comparison, an overview of fiber Bragg gratings will be also presented.

2.3.1 PHASE-MATCHING CONDITION

Fiber Bragg gratings or FBGs, first discovered in 1978, were based on phase-matching between the forward propagating and backward propagating LP_{01} guided core mode in the presence of a periodic modulation of refractive index in the core of the optical fiber [43]. Figure 2.7 is a graphic representation of the backward propagation core mode in a FBG.

Figure 2.7 A graphic representation of fiber Bragg gratings.

From the phase-matching equation, the propagation constant for β_1 and β_2 of equation 2.6 can be written as,

$$\beta_1 = n_{core}^{eff} k \quad (2.14)$$

$$\beta_2 = -\beta_1 = -n_{core}^{eff} k \quad (2.15)$$

where n_{core}^{eff} is the effective refractive index in the core of the optical fiber and $k = \frac{2\pi}{\lambda}$

is the free-space propagation constant. The negative sign in equation 2.15 indicates propagation in the opposite direction. By substituting equations 2.14 and 2.15 into equation 2.6, the equation becomes,

which yields the well-known Bragg equation or phase-matching equation for fiber Bragg gratings,

$$\lambda_{res} = 2n_{core}^{eff} \Lambda \quad (2.17)$$

where λ_{res} and Λ are the reflected Bragg wavelength and grating period respectively.

Equation 2.17 shows that the Bragg wavelength is directly proportional to the grating period and hence any changes in the latter will result in a change in the reflected Bragg wavelength. The characteristic curve of the FBG can be obtained by differentiating equation 2.17 and the result is shown in figure 2.8,

$$\frac{d\lambda}{d\Lambda} = 2n_{core}^{eff} \quad (2.18)$$

Figure 2.8 Characteristic curve of FBG showing the relationship between grating period and the reflected Bragg wavelength.

Figure 2.8 shows that the coupling wavelength of an FBG has a linear relationship with the grating period. This implies that an incremental change in the grating period produces approximately the same variation in the Bragg wavelength at all values of the grating period.

Figure 2.9 Mode coupling mechanism in fiber Bragg grating shows that large value of $\Delta\beta$ required small grating periodicity to study the phase-matching condition.

By adopting the β -plot, the grating periodicity of an FBG can be obtained. Figure 2.9 shows that an FBG under phase-matched condition resulted in large $\Delta\beta$, which means a small grating period is required. Typical grating period for optical communication lies between 524 nm and 559 nm.

2.3.2 PRINCIPLE OF OPERATION

The initial use of FBG is in the area of optical communications as an optical filter in Dense Wavelength Division Multiplexing (DWDM) network, fiber amplifier, dispersion compensation, tunable filter and external cavity laser diodes [45]. Reference [45] gives an excellent overview of the applications of FBG in optical communications as well as sensing.

Beside its application in optical communications, the FBG has also been used for sensing applications. Being sensitive to external perturbations, such as temperature and strain, the Bragg wavelength of the FBG fluctuates with these perturbations. Thus, this poses a problem in optical communications and therefore compensation has to be incorporated in order to compensate for the errors due to these perturbations. These

disadvantages however make FBG an excellent optical fiber sensor device, suitable for measuring static and dynamic fields, such as temperature, strain and pressure [46]. Since the FBG sensor's response to perturbations is wavelength encoded, these perturbations are measured by measuring the amount of shift in the reflected Bragg wavelength with respect to the original value. Although measurements of FBG sensor's response include measuring the transmitted or reflected FBG spectrum, in most cases, measuring the reflected Bragg wavelength is preferred as this allows the configuration of single-ended probe sensors, making it convenient to use in confined spaces. The basic FBG sensor setup is shown in figure 2.10.

Figure 2.10 A common configuration of FBG sensor setup.

An optical circulator, in figure 2.10, is an optical device that allows light to be transmitted from port 1 to port 2 but redirects any reflected light from port 2 to port 3. The Bragg wavelength's response to external perturbation from the FBG sensor, figure 2.10, is monitored through an optical spectrum analyzer via port 3 of the optical circulator.

From equation 2.17, the Bragg wavelength is dependent on the effective refractive index of the core and the periodicity of the grating. The effective refractive index, as well as the periodic spacing between the gratings, is affected by changes in

strain and temperature. Differentiating eq. 2.17 with respect to external perturbation P yields,

$$\Delta\lambda = 2 \left(\Lambda \frac{\partial n_{eff}}{\partial P} + n_{eff} \frac{\partial \Lambda}{\partial P} \right) \Delta P \quad (2.19)$$

Equation 2.19 corresponds to a change in the grating spacing and induced change in the refractive index due to either strain or temperature, where $P = \varepsilon$ for strain and $P = T$ for temperature. In the event of strain, equation 2.19 is express as [46],

$$\Delta\lambda = \lambda(1 - \rho_e)\varepsilon_z \quad (2.20)$$

where ρ_e is an effective strain-optic constant defined as,

$$\rho_e = \frac{n_{eff}^2}{2} [\rho_{12} - \nu(\rho_{11} + \rho_{12})] \quad (2.21)$$

where ρ_{11} and ρ_{12} are components of the strain-optic tensor, and ν is the Poisson's ratio. For typical germanosilicate optical fiber, $\rho_{11}=0.113$, $\rho_{12}=0.252$, $\nu=0.16$ and $n_{eff}=1.482$. Hence using these parameters and equations 2.20 and 2.21, the estimated strain sensitivity at ~ 1550 nm is a 1.2 pm change resulting from applying 1 $\mu\varepsilon$ to the FBG. Figure 2.11 shows the wavelength response of the FBG sensor with compression force. This result came from the experiment studies using FBG sensor as a gauge for measuring compression stress on cylindrical concrete structures under compression stress.

Figure 2.11 Experimental results of compression test on concrete cylinder with surface mounted FBG sensor.

For a temperature induced Bragg wavelength change, equation 2.19 would be written as [46],

$$\Delta\lambda = \lambda_{res} (\alpha_A + \alpha_n) \Delta T \quad (2.22)$$

where $\alpha_A = (1/\lambda)(\partial\lambda/\partial T)$ is the thermal expansion coefficient for the fiber (approximately 0.55×10^{-6} for silica). The $\alpha_n = (1/n_{eff})(\partial n_{eff}/\partial T)$ represents the thermo-optic coefficient, which is approximately 8.6×10^{-6} for the germania-doped, silica core fiber. It can be observed that index change due to temperature is the dominant effect. From equation 2.22, the sensitivity for a FBG with the Bragg wavelength center at 1550 nm is approximately 13.7 pm/°C. Figure 2.12 shows an experimental result of a FBG Bragg wavelength response as a function of temperature.

Figure 2.12 Measurement of reflection Bragg wavelength shift with temperature.

Although the FBG sensor is able to detect numerous perturbations, there are cases where detection is possible only through modifying the physical structure of the optical fiber. For example, when using FBG sensor for refractive index sensing, the fiber cladding has to be etched to a distance close to the fiber core in order to gain access to the light propagating in it [48, 49, 50]. Referring back to the Bragg equation (2.17), the back-reflected Bragg wavelength is a function of both the grating period Λ and the core effective refractive index n_{core}^{eff} . The core effective refractive index is dependent on the external medium refractive index, which will vary with different external medium refractive index. This change in n_{core}^{eff} will result in a change of the Bragg wavelength. To induce a n_{core}^{eff} change in an FBG refractive index sensor, the cladding has to be etched or polished down close to the core before covering the etched portion with the external medium to be tested. The downside of this technique is that the structural integrity of the optical fiber will be affected rendering the FBG sensor unsuitable to be used in harsh environment.

This problem however can be overcome with the use of another class of fiber grating sensor, namely long period grating sensor or LPG sensor. Like the FBG, the LPG contains a modulation of refractive index along the core of the fiber, except that the grating period is in the range of 100 μm to 1000 μm . Unlike an FBG, the core mode propagating in the optical fiber core will be coupled into discrete cladding modes travelling in the cladding region in the same direction as the core mode. At the cladding/air interface of the optical fiber, any changes in external medium refractive index surround the cladding will result in changes of the optical characteristics of the cladding modes. The changes in optical characteristics can be in the form of changes in the wavelength or intensity. By using LPG sensor for refractive index measurement, no etching of the cladding is required and hence the structural integrity of the optical is preserved. In the next section, the fundamental operating principle governing the LPG sensing characteristics will be discussed.

2.4

LONG PERIOD GRATINGS

Before embarking on the description of LPG fabrication and sensing applications, we will first discuss the principle concepts that govern the operation of an LPG. This primary concepts discussed includes the phase matching condition, the LPG characteristic curves and the coupling coefficient.

2.4.1 PHASE-MATCHING CONDITION

In an LPG, the gratings that allow the transfer of power between the fundamental core mode and cladding modes follow a phase-matching condition. From equation 2.6, and with $\beta_1 = n_{core}^{eff}(\lambda)$ and $\beta_2 = n_{cl,m}^{eff}(\lambda)$, the phase-matching condition can be rewritten as,

$$\lambda_{res} = \left(n_{core}^{eff}(\lambda) - n_{cl,m}^{eff}(\lambda) \right) \Lambda \quad (2.23)$$

where λ_{res} is the resonance wavelength, n_{core}^{eff} is the effective refractive index of the core mode and $n_{cl,m}^{eff}$ is the effective refractive index of the m th cladding mode. The wavelength dependence of the effective refractive indices is due to material and waveguide dispersion. Differentiating equation 2.23 yields,

$$\frac{d\lambda_{res}}{d\Lambda} = \frac{\left(n_{core}^{eff}(\lambda) - n_{cl,m}^{eff}(\lambda) \right)}{\left\{ 1 - \Lambda \frac{d \left(n_{core}^{eff}(\lambda) - n_{cl,m}^{eff}(\lambda) \right)}{d\lambda_{res}} \right\}} \quad (2.24)$$

From equation 2.24, the resonance wavelength of a cladding mode, as a result of the coupling from the core mode, can be predicted by a particular period. The first step of prediction involves the calculation of the effective refractive indices of the fundamental core mode and the various resonant cladding modes of the fiber for a specific wavelength. A set of grating periods $\Lambda^{(m)}$ is obtained that will meet the matching condition given by equation 2.23. This step is then repeated for several different wavelengths. The plot as shown in figure 2.13 depicts mode coupling of the core mode to azimuthally symmetric cladding modes with uniform refractive index perturbations perpendicular to the direction of propagation [51]. From the plot, a grating period can be chosen so as to allow mode coupling to take place at any desire wavelength. Furthermore the choice of $\Lambda^{(m)}$ also allows the separation between two the cladding modes to be varied. These plots are also known as the LPG characteristic curves, which will be discussed in the later section of this chapter.

Fig. 2.13 Phase plot of resonant cladding modes for a step index optical fiber. Lower order modes are to the right [51].

2.4.2 PRINCIPLE OF OPERATION

The principle of operation of LPG proposed by Vengsarkar *et al.* in 1996 [40] is illustrated in figure 2.14.

Figure 2.14 Mode conversion of a fundamental core mode into a forward propagating cladding mode in an optical fiber with long period grating inscribed.

Guided light in the fundamental LP_{01} core mode is perturbed by the presence of the gratings in the fiber core. The difference between the propagation constant of the guided core mode and the phase-matching vector of the grating equals the propagation constant of one or more cladding modes at the appropriate wavelengths. Cladding modes are then guided in the cladding region along the cladding-air interface and the modes attenuate rapidly due to bends in the optical fiber and absorption by the cladding material. Therefore energy of the cladding mode at the phase-matched wavelength is lost from the fiber. The result is series of resonance dips or bands in the LPG transmission spectrum as shown in figure 2.6. An interesting feature about LPG is the resonance dips' sensitivity to external medium surrounding the LPG region. The effective refractive index of the m th cladding mode ($n_{cl,m}^{eff}(\lambda)$) in equation 2.23 is dependent on the refractive index of the external medium. This affects the differential effective mode index and therefore the spectral resonance dip corresponding to that m th cladding mode. This feature makes the LPG an attractive sensor for refractive index, chemical and biomedical sensing.

The basic operating principle of the LPG can also be illustrated using β -plot for the simplified mode coupling mechanism in a LPG, as shown in figure 2.15.

Figure 2.15 β -plot of mode coupling mechanism in a LPG.

From the β -plot, the forward propagating guided core mode with the propagation constant β_{01} couples light to the azimuthally-symmetric cladding modes, with propagation constants that fall in the range $\omega n_3/c < \beta^{(m)} < \omega n_2/c$, traveling in the same direction. $\Delta\beta^{(m)}$ is the differential propagation constant and Λ is the grating periodicity, which are defined in equation 2.6. The small value of $\Delta\beta^{(m)}$ requires the grating period to be much larger than that for fiber Bragg gratings, in the range between 100 μm to 1000 μm . For a typical LPG, more than one cladding modes would satisfy the phase-matching condition, but at different wavelengths, and be coupled from the guided mode to all these lossy cladding modes. The spectral dependence of the propagation constants of the core and cladding modes results in a highly wavelength-selective response of the LPG, figure 2.6. The figure depicts the effect of coupling the fundamental core mode to discrete cladding modes resulting in distinct resonance dips in the transmission response. The resonance dips have different peak loss and bandwidth due to dissimilar coupling coefficients that are functions of the modal overlap. The concept of coupling coefficient and its relation with the modal overlap will be covered in section 2.4.3.2. Figure 2.16 shows the intensity distribution measured by the near-field technique for a group of cladding modes [52].

Figure 2.16 Near-field intensity distribution of LP_{0m} cladding modes with (a) $m=4$, (b) $m=5$, (c) $m=6$, (d) $m=7$ [52].

For a standard optical fiber, such as Corning SMF-28, the differential effective refractive index between the guided core and cladding modes is from 10^{-3} to 10^{-2} . If the coupling is to occur at wavelengths in the optical communication window (1520 nm – 1620 nm), the period of the gratings are in hundreds of micron. Comparing with an FBG, an LPG does not contain any reflected resonance wavelength. The only slight reflection is caused by Fresnel reflections at the end of the optical fiber due to refractive index discontinuities in the core [40].

2.4.3 CHARACTERISTIC OF LONG PERIOD GRATINGS

For an understanding of the characteristic of an LPG, this section will look into the various parameters. One of the parameters is the characteristic curves of an LPG, which relate the various sets of grating periods that would induce coupling between the fundamental core mode into various discrete cladding modes. Next parameter to be discussed will be the coupling coefficient, which is dependent on the refractive index change in the core, and the modal overlap between the core mode and cladding modes.

2.4.3.1 CHARACTERISTIC CURVES OF LONG PERIOD GRATINGS

From the phase-matching equation (2.23), the latter can be rewritten as,

$$\delta n_{eff} \Lambda = \lambda_{res} \quad (2.25)$$

where $\delta n_{eff} = (n_{core}^{eff}(\lambda) - n_{cl,m}^{eff}(\lambda))$.

To simplify the analysis, the ordinal m has been dropped, which represents the order of the cladding mode. Since the δn_{eff} is a function of operating wavelength, differentiating both sides of equation 2.25 with respect to the wavelength λ yields,

$$\frac{d\Lambda}{d\lambda} = \frac{\delta n_{eff} - \lambda \left[\frac{dn_{eff}}{d\lambda} \right]}{(\delta n_{eff})^2} \quad (2.26)$$

We define the group index of the core mode ($n_{co,g}$) and the cladding mode ($n_{cl,g}$) as [53],

$$n_{co,g} = n_{core}^{eff} - \lambda \frac{dn_{core}^{eff}}{d\lambda} \quad (2.27)$$

and

$$n_{cl,g} = n_{cl}^{eff} - \lambda \frac{dn_{cl}^{eff}}{d\lambda} \quad (2.28)$$

By substituting equations 2.27 and 2.28 into equation 2.26, an expression for the slope of the coupling wavelength versus the grating period curve is obtained [54],

$$\frac{d\lambda}{d\Lambda} = \frac{(\delta n_{eff})^2}{\delta n_g} \quad (2.29)$$

where $\delta n_g = n_{co,g} - n_{cl,g}$

Equation 2.29 suggests that the slope of the coupling wavelength versus grating period is dependent on both the differential effective refractive index between the effective refractive index of the core mode and the cladding mode, δn_{eff} , and also the differential group index, δn_g . The wavelength versus period curves are termed the characteristic curves of an LPG. As δn_{eff} and δn_g are functions of the parameters of the optical fiber in which the gratings are fabricated, the characteristic curves are therefore dependent on the properties of the host fiber [54].

In order to determine the relationship between the resonance wavelengths and the period of the long period grating, the spectral dependency of the effective refractive indices of the core and cladding have to be known. Since these parameters are functions of the core and cladding refractive indices, it is important to include the material variation of the fiber. A simple technique to calculate the change in the core and cladding refractive indices with wavelength, if the germania concentration in the core is known, is to approximate the refractive index $n(\lambda)$ as a function of wavelength λ for a particular material using the Sellmeier equation [55],

$$n^2(\lambda) = 1 + \sum_{i=1}^M \frac{A_i \lambda^2}{\lambda^2 - \lambda_i^2} \quad (2.30)$$

where A_i and λ_i are material-dependent parameters. The parameters in the Sellmeier equation for bulk glass samples of different composition is summarized in table 2.1 [56].

Composition	A_1	A_2	A_3	$\lambda_1 (\mu m)$	$\lambda_2 (\mu m)$	$\lambda_3 (\mu m)$
Quenched SiO_2	0.696750	0.408218	0.890815	0.069066	0.115662	9.90059
13.5% GeO_2 : 86.5% SiO_2	0.711040	0.451885	0.704048	0.064270	0.129408	9.425478

Table 2.1 Sellmeier parameters for bulk glass samples of different composition [56].

For most applications, only the first three terms ($M=3$) are necessary to obtain an accuracy of about 10^{-5} in refractive index calculations. Table 2.1 lists the first three Sellmeier parameters for a quenched sample of silica with 13.5% GeO_2 and 86.5% SiO_2 . The cladding in the majority of standard optical fibers is made of quenched silica, whereas the core consists typically of quenched silica with an appropriate doping of GeO_2 . So far, the values of the Sellmeier parameters are available for only a few specific GeO_2 concentrations, but the refractive index variation for intermediate

doping concentrations can be calculated through the interpolation of the given parameters [57]. For example, the Sellmeier parameters for a quenched sample of 6.75 % GeO_2 and 93.25 % SiO_2 can be approximated by averaging the values given in table 2.1.

Figure 2.17 Characteristic curves for the first ten cladding modes in SMF-28 [54]. The dashed curve corresponds to cutoff wavelength (λ_{cut}) for different period.

Figure 2.17 shows the characteristic curves for $m=1$ cladding mode to $m=10$ cladding mode. The dashed curve is the cut-off wavelength or the minimum wavelength at which coupling can occur to a cladding mode at a given period. The cut-off wavelength is calculated at each value of the grating period by using the phase-matching condition and increases with periodicity. From the figure, the resonance wavelengths are located at values larger than this minimum wavelength. For a fixed grating period, the coupling wavelength is an increasing function of the cladding mode order. In addition, the wavelength separation between the resonance wavelengths increases with the order of the corresponding cladding modes. During fabrication of

the LPG, figure 2.17 helps give an approximate estimation as to the location of the resonance wavelength for a given period. However this condition varies with different types of optical fiber used.

It can be observed that for higher order modes $m > 9$, the slope of the corresponding curves approaches infinity at the wavelength higher than 1500 nm. This can be explained on the basis of the differential refractive index difference between the guided mode and cladding modes that operate in the positive dispersion region of the spectrum [54]. For $m < 9$, the area where the slope of the curves are positive is termed the normal region and the slope at which $\frac{d\lambda_{res}}{d\Lambda} = \infty$ is termed the turning point for the m th cladding mode. The wavelength at which this occurs is termed the equalization wavelength λ_e . Beyond that the slope becomes negative and this region is named the anomalous region [54, 58].

The polarity of the slope has an effect of the direction of the resonance wavelength shift when there is a change in the refractive index or the grating period. In the normal region, where $\frac{d\lambda_{res}}{d\Lambda} > 0$ and using equation 2.23, the resonance wavelength will shift to the higher values as the core refractive index is increased during grating fabrication, while the resonance wavelength will shift to the lower value when the effective refractive index of the m th cladding mode increases. The reverse will occur when operating in the anomalous region, where $\frac{d\lambda_{res}}{d\Lambda} < 0$ and using equation 2.23. For operation in the anomalous region, a smaller grating period is required as compared to the operation in the normal region. Due to the ease of

fabrication using larger grating period and lower cost in fabricating the amplitude masks that have larger periods, most LPG operates in the normal region. All LPG sensors developed for this project work were fabricated using conditions in the normal region.

By comparing the characteristic curves of the LPG, figure 2.17, with the characteristic curves of the FBG, figure 2.8, a difference is noted. Spectral shift due to an induced strain or temperature on FBG or LPG is a function of the slope of the FBG or LPG characteristic curves. Since this slope is constant for all grating periods in the FBG, the waveguide contribution is the same at all wavelengths. On the other hand, the waveguide contributions to strain and temperature sensitivity in the LPG are functions of the grating period for coupling to the same cladding mode.

2.4.3.2 COUPLING COEFFICIENT

It was mentioned in section 2.4.2 that the resonance dips have different peak loss due to dissimilar coupling coefficients that are functions of the modal overlap. In the previous section (2.4.3.1), the LPG characteristic curves describe the effect of external influences, such as the fabrication process, refractive index of external medium or change in grating period, have on the spectral location of the resonance wavelengths in the transmission spectrum. In addition to the resonance wavelength change, the degree of loss of the resonance dips in the LPG spectrum will also be affected by these external influences [59, 60, 61], which is related to the coupling coefficients. Hence the coupling coefficient in the LPG is as important as that of the characteristic curves.

From equation 2.9, the coupling between two the modes in the same direction is a strong function of the detuning ratio $\frac{\delta}{\kappa}$, where δ is the detuning parameter and κ is the coupling coefficient of the grating. The detuning parameter is dependent on the proximity of the operating wavelength to the phase-matching wavelength of the grating. The coupling coefficient is a function of the index change and the modal overlap between the guided core mode and the cladding modes over the region of perturbation, according to figure 2.5. For maximum power transfer, the value of the detuning ratio has to be minimum and ideally zero.

The expression for the coefficient can be defined by using the approach adopted by A. W. Snyder and J. D. Love [62]. The periodic modulation of refractive index in the core of the optical fiber can be represented by the function $\delta n(z)$. Hence the modified refractive index profile in the core is $n(z)$ such that [61],

$$n(z) = n_l + \delta n(z) \quad (2.31)$$

where n_l is the unperturbed core refractive index. The periodic modulation of refractive index $\delta n(z)$, assumed to be rectangular, can be expressed as [53],

$$\delta n(z) = \Delta n \text{rect}\left(\frac{z}{\Lambda}\right) \quad (2.32)$$

where Λ is the grating period, and for a 50 % duty cycle, the $\text{rect}\left(\frac{z}{\Lambda}\right)$ function is given by,

$$\text{rect}\left(\frac{z}{\Lambda}\right) = 1 \quad \text{for } q\Lambda < z < \left(q + \frac{1}{2}\right)\Lambda \quad (2.33a)$$

$$\text{rect}\left(\frac{z}{\Lambda}\right) = 0 \quad \text{for } \left(q + \frac{1}{2}\right)\Lambda < z < (q+1)\Lambda \quad (2.33b)$$

where q is an integer. The periodic variation in the index can be expressed in terms of its Fourier series by,

$$\delta n(z) = \Delta n \left[A_0 + \sum_{N=1}^{\infty} A_N \cos\left(\frac{2\pi N}{\Lambda} z\right) \right] \quad (2.34)$$

where Δn is the peak change in refractive index and A_N are the Fourier coefficients.

The coupling coefficient κ is given by the square root of the product of the two cross-coupling coefficients, κ_{12} and κ_{21} such that [62],

$$\kappa = \sqrt{\kappa_{12}\kappa_{21}} \quad (2.35)$$

where the subscripts 1 and 2 represent the guided and the cladding modes respectively.

The cross-coupling coefficients are functions of the order of the mode m and is given by [62],

$$\kappa^m = \frac{k |A_N|}{2} \frac{\left| \int_0^a \Delta n E_{0l}(r) E_{cl}^m(r) r dr \right|}{\sqrt{\int_0^{\infty} (E_{0l}(r))^2 r dr \int_0^{\infty} (E_{cl}^m(r))^2 r dr}} \quad (2.36)$$

where $k = \frac{2\pi}{\lambda^m}$. $E_{0l}(r)$ and $E_{cl}^m(r)$ are the electric field distribution of the fundamental guided mode and the circularly-symmetric cladding mode of order m respectively. The integration in the numerator is over the core only since the refractive index perturbation for the grating is confined to the fiber core. Defining the overlap integral η^m as,

$$\eta^m = \frac{\left| \int_0^a \Delta n E_{0l}(r) E_{cl}^m(r) r dr \right|}{\sqrt{\int_0^{\infty} (E_{0l}(r))^2 r dr \int_0^{\infty} (E_{cl}^m(r))^2 r dr}} \quad (2.37)$$

the coupling coefficient can be rewritten as,

$$\kappa^m = \frac{\pi |A_N|}{\lambda^m} \eta^m \quad (2.38)$$

where it has been assumed that the coupling coefficient is constant across the spectral width of a resonance dip of order m and centered at λ^m . It is evident from equation 2.38 that the coupling coefficient is inversely proportional to the coupling wavelength and directly proportional to the order of the cladding mode, the change in refractive index in the core and the overlap integral. Since it is directly proportional to the overlap integral, the modal distribution of the cladding mode will have a strong influence on the magnitude of coupling. In addition, since the refractive index modulation has no azimuthal variation, the coupling of the guided mode can occur only to circularly-symmetric cladding modes, and for all other cladding modes, the overlap integral is zero.

The amplitude mask used in the fabrication process of the LPG is a rectangular metallic mask with a 50 % duty cycle. Hence the Fourier series of the rectangular refractive index modulation with a grating period of Λ can be expressed as [62],

$$\delta n(z) = \Delta n \left[\frac{1}{2} + \frac{2}{\pi} \sum_{N=1}^{\infty} \frac{1}{N} \sin\left(\frac{N\pi}{2}\right) \cos\left(\frac{2\pi N}{\Lambda} z\right) \right] \quad (2.39)$$

By comparing equation 2.39 with equation 2.34, the Fourier coefficients ($N > 1$) are given by,

$$A_N = \frac{2}{N\pi} \sin\left(\frac{N\pi}{2}\right) \quad (2.40)$$

For $N=1$ the Fourier coefficient is $A_1 = \frac{2}{\pi}$. It is noted that $A_2 = 0$ and for a LPG with a perfect rectangular refractive index modulation of 50 % duty cycle, the second-order interaction between the guided and the cladding modes does not exist. As the coupling coefficient scales inversely with the order of N , the higher order interactions can also

be neglected for a simplified analysis. Thus the coupling coefficient for the first order interaction in a LPG with rectangular refractive index modulation is given by,

$$\kappa^m = \frac{2}{\lambda^m} \eta^m \quad (2.41)$$

Since the overlap integral is a dimensionless quantity, the coupling coefficient is expressed in the units of per unit length (typically cm^{-1}). For an LPG, the refractive index modulation created during the fabrication process makes the coupling coefficient a function of the transmittance function of the amplitude mask and the peak refractive index change. It is important to note that to obtain the exact values of the coupling coefficient, the presence of the core has to be included while analyzing the cladding modes. The reason is that the coupling coefficient includes the overlap between the guided and the cladding modes in the fiber core and neglecting the presence of the core during cladding mode analysis can result in large discrepancies between the actual and calculated values [62].

2.4.3.3 TRANSMISSION OF LONG PERIOD GRATINGS

From section 2.2.1, the expression for the power coupled for one forward-propagating mode to another in the presence of a perturbation has been discussed. The coupling ratio C of the power coupled to a cladding mode of order m to the initial power in the fundamental guided mode is hence approximated by [54],

$$C = \frac{P^m(L)}{P_{01}(0)} = \frac{\sin^2 \left[\kappa^m L \sqrt{1 + \left(\frac{\delta^m}{\kappa^m} \right)^2} \right]}{1 + \left(\frac{\delta^m}{\kappa^m} \right)^2} \quad (2.42)$$

where L is the length of the grating and κ^m and δ^m are the coupling coefficient and detuning parameter for the corresponding cladding mode, respectively. The detuning parameter at a wavelength λ is defined as,

$$\delta^m = \frac{1}{2} \left(\beta_{0l} - \beta^m - \frac{2\pi}{\Lambda} \right) = \frac{\pi}{\Lambda} \frac{(\lambda^m - \lambda)}{\lambda^m} \quad (2.43)$$

and is zero at the phase-matching wavelength λ^m . As mentioned previously, for maximum power transfer from the guided mode to cladding mode, the magnitude of the detuning ratio, $\frac{\delta^m}{\kappa^m}$ should be kept zero. The normalized power T transmitted by the fundamental guided mode through the grating is given by [54],

$$T = \frac{P_{0l}(L)}{P_{0l}(0)} = \frac{\cos^2 \left[\kappa^m L \sqrt{1 + \left(\frac{\delta^m}{\kappa^m} \right)^2} \right] + \left(\frac{\delta^m}{\kappa^m} \right)^2}{1 + \left(\frac{\delta^m}{\kappa^m} \right)^2} \quad (2.44)$$

Thus at the phase-matched wavelength, equation 2.43 and equation 2.44 will be reduced to,

$$C = \sin^2(\kappa^m L) \quad (2.45)$$

$$T = \cos^2(\kappa^m L) \quad (2.46)$$

Hence, it is shown that at phase-matched wavelength, equation 2.45 gives the maximum value of $C=1$, which is the degree of transfer of power, and equation 2.46 gives the minimum power in the transmitted guided mode $T=0$, for a fixed grating length.

From equation 2.45, the coupling strength $\kappa^m L$ is maximum when $(\kappa^m L) = \frac{\pi}{2}$

and will oscillate between 0 and 1, when $(\kappa^m L) < \frac{\pi}{2}$ or $(\kappa^m L) > \frac{\pi}{2}$. The effect is

apparent during the fabrication of LPG such that during the exposure of the UV-laser, the resonance dip in the transmission spectrum increases initially for $(\kappa^m L) < \frac{\pi}{2}$. The loss is at maximum when $(\kappa^m L) = \frac{\pi}{2}$. For $(\kappa^m L) > \frac{\pi}{2}$, the power in the cladding mode starts to couple back into the fundamental core mode, leading to an increase of the guided mode transmitted power and a reduction in the coupling ratio. More details on the fabrication process will be discussed in chapter 3.

2.5 EFFECTS OF EXTERNAL PERTURBATION ON LONG PERIOD

GRATINGS

Similar to the FBG, the original applications of LPG and even till today, is optical fiber-based devices for optical communications such as EDFA gain equalizer, optical filter, mode coupler, etc. However in the recent years, more focus has been placed in LPG research for sensing application. This is due to the sensitivity of LPG to external perturbations such as temperature, strain and refractive index of surrounding medium. This section will discuss the LPG spectral response to temperature, strain and refractive index of surrounding external medium.

2.5.1 TEMPERATURE ON LONG PERIOD GRATING

The dominating effect of temperature change on the transmission spectrum of the LPG is the temperature-induced shift in the resonance wavelength. Using the chain rule of derivatives, the sensitivity to a temperature T for a grating of length L can be obtained from equation 2.23.

$$\frac{d\lambda_{res}}{dT} = \frac{d\lambda_{res}}{d(\delta n_{eff})} \left[\frac{dn_{core}^{eff}}{dT} - \frac{dn_{cl,m}^{eff}}{dT} \right] + \Lambda \frac{d\lambda_{res}}{d\Lambda} \frac{1}{L} \frac{dL}{dT} \quad (2.47)$$

Equation 2.47 shows that there are two factors affecting the temperature sensitivity of the LPG resonance wavelength, namely,

1. Material contribution due to the change in the differential refractive index of the core and cladding arising from the thermo-optic effect.
2. Waveguide contribution due to the change in the grating periodicity due to the thermal expansion of the fiber.

For the material contribution, Bhatia [64] reported that the material contribution is dependent upon the composition of the fiber and the order of the cladding mode. For the same type of fiber, the order of cladding mode determines if the material contribution dominates. For a fixed resonance wavelength, equation 2.23 shows that the coupling to a higher cladding mode (lower cladding effective refractive index) requires smaller grating periods. For grating periods greater than 100 μm , in standard germanosilicate fiber, the coupling will be to the lower order cladding modes and the material contribution dominates. On the other hand, the material contribution becomes negligible when core mode is coupled to higher order cladding modes using grating periods that are less than 100 μm [64, 65].

For the case of waveguide contribution, the magnitude and sign are also dependent on the coupled order of the cladding mode. When the coupling is to the lower cladding modes, $\frac{d\lambda_{res}}{dT}$ will be positive while for the higher cladding modes, $\frac{d\lambda_{res}}{dT}$ will be negative [64, 65]. Figure 2.18 shows different wavelength shift of four resonance dips of an LPG [64].

Figure 2.18 Different gradients of the slope show that different order of the cladding has different sensitivity to temperature change. The location of the bands A, B, C and D are 1608.6 nm, 1332.9 nm, 1219.7 nm and 1159.6 nm, respectively at 31.2°C. The dashed line (E) is the shift for a Bragg grating at 1550 nm with a temperature coefficient of 1.3 nm/100 °C [64].

By appropriate choice of grating period, it is possible to balance out the material contribution with waveguide contribution, and yield a temperature independent LPG sensor. Bhatia [64] has fabricated a near-temperature insensitive LPG sensor, with grating period of 40µm, which exhibits a temperature sensitivity of only 1.8 pm/°C. For a normal LPG, fabricated with standard germanosilicate fiber and having gratings period around 200 µm to 500 µm, the temperature sensitivity is approximately 30 pm/°C [65].

The temperature sensitivity of a LPG sensor is dependent not only on the orders of the cladding mode but also the material of optical fiber used. LPG fabricated on standard germanosilicate fiber exhibits a temperature sensitivity of 3 nm/100°C to

10 nm/ °C. On the other hand, LPG fabricated with B-Ge co-doped fiber exhibits a temperature sensitivity of 275 nm/ °C [66]. Hence for a LPG temperature sensor, B/Ge co-doped fiber would be a better choice.

2.5.2 STRAIN ON LONG PERIOD GRATING

The effect of strain on the transmission spectrum of the LPG results in a shift of its resonance wavelength. Like the FBG, in which the Bragg wavelength is proportional to the grating period multiplied by the refractive index of the core, the LPG wavelength is proportional to the grating period and the effective refractive index difference between the core and the cladding.

The expression to describe the change of resonance wavelength with strain is as [53],

$$\frac{d\lambda_{res}}{d\varepsilon} = \frac{d\lambda_{res}}{d(\delta n_{eff})} \left[\frac{dn_{core}^{eff}}{d\varepsilon} - \frac{dn_{cl,m}^{eff}}{d\varepsilon} \right] + \Lambda \frac{d\lambda_{res}}{d\Lambda} \quad (2.48)$$

where ε is the induced strain. Two terms on the right side of equation 2.48 can be divided into the material contribution and the waveguide contribution. The material contribution is attributed to strain induced change in the difference in the effective refractive index and the order m of the cladding mode. The waveguide contribution depends on the grating period with strain and the order of the cladding mode. Bhatia had suggested that the material contribution is negative and this is due to the overall changes in the core and cladding refractive indices and radii. As a result, these changes will produce an overall reduction in the difference of the effective refractive index at the particular cladding mode [54]. As for the waveguide contribution, the latter increases with cladding mode order as higher cladding mode order have higher slopes

$\frac{d\lambda_{res}}{d\Lambda}$ for a fixed grating period. The waveguide contribution will be more pronounced for higher cladding mode for a fixed grating period.

Under normal operation, Bhatia has shown that the lower cladding modes of an LPG will shift to a shorter wavelength under axial strain. This negative shift is due to the small slope, $\frac{d\lambda_{res}}{d\Lambda}$, of the characteristic curve for the respective cladding modes and therefore a domination of the negative waveguide contribution. The waveguide contribution, on the other hand, increases with order of cladding mode. Figure 2.19 shows the strain sensitivity of different order cladding modes [54].

Figure 2.19 Graph shows the wavelength shift between LPG for different cladding mode (solid line) and FBG (dashed line) under strain. The location of A, B, C, D are 1607.8 nm, 1332.4 nm, 1219.3 nm and 1159.3 nm [54].

By careful selection of cladding mode order, one can balance the effect of material contribution with waveguide contribution, making the LPG strain insensitive. The selection of cladding mode can be achieved by proper selection of grating period. Strain insensitive LPG is particularly useful in temperature sensing application as LPG is sensitive to both temperature and strain.

2.5.3 EXTERNAL REFRACTIVE INDEX ON LONG PERIOD GRATING

This is an interesting characteristic of long period grating, in which the latter has the capacity to measure the refractive index of the external medium without the need to etch away the cladding region to get to the core. The reason is evident from the phase-matching condition of equation 2.23. Equation 2.23 depicts that the effective refractive index of the m th cladding mode is dependent on the difference between the refractive indices of the cladding and the external medium surrounding the LPG region. Thus under the condition that the external medium refractive index is lower than that of cladding, any changes in the external medium index will cause a final change in the spectral location of the LPG's resonance wavelength. The ability of the cladding modes to respond to the presence of the external medium is due of the evanescent fields of the cladding modes that penetrate beyond the cladding-surrounding interface.

If the external medium refractive index increases, the effective refractive index of the m th cladding mode increases. According to equation 2.23, this will render the shift of the LPG resonance wavelength to a lower spectral location, i.e. a blue shift, provided the final refractive index of the external medium is lower than that of cladding [67]. Patrick *et al.* also showed that changes in the external medium refractive index also affects the depth of the LPG resonance dips and is more prominent when the external medium refractive index is closer to that of cladding, see figure 2.20. Figure 2.20 shows that when the external medium index increases beyond a value of 1.4 and approaches that of cladding, which is approximately 1.46, the depth of the LPG resonance dip reduces drastically. This characteristic of a big change in the resonance dip with small change in the external medium index makes LPG a highly

sensitive refractive index sensor working in the region where index is close to that of cladding.

Figure 2.20 Top graph shows the LPG resonance wavelength response to external index change. Bottom graph shows the effect of external index on the peak loss of the LPG resonance dip [67].

The expression to describe the change in the resonance wavelength resulting from the change in external medium refractive index is shown as,

$$\frac{d\lambda_{res}}{dn_{ext}} = \frac{d\lambda_{res}}{dn_{eff}^{cl,m}} \left[\frac{dn_{eff}^{cl,m}}{dn_{ext}} \right] \quad (2.49)$$

Equation 2.49 depicts the change in the LPG resonance wavelength with change in the external medium refractive index but the sensitivity of the LPG is dependent on the order of the coupled cladding mode. Higher index sensitivity can be achieved with higher order of the cladding modes as these modes are less bound to the fiber waveguide itself [65, 67].

What have been discussed above so far is a situation whereby the external medium refractive index is lower than that of cladding. In this situation, the phase-matching condition in the LPG maintains its validity. As the external medium refractive index increases beyond that of the cladding, the LPG transmission spectrum responds differently.

In the case where the external medium refractive index matches that of cladding, the discrete cladding modes are no longer guided along the fiber. This is evident in the absence of the resonance dip in the LPG transmission spectrum as shown in figure 2.20 and figure 2.21.

Figure 2.21 Experimentally measured core mode transmission losses for several refractive indexes surrounding the LPG.

It has been experimentally demonstrated that, from figure 2.21, when the external medium refractive index matches that of cladding, $n_{ext} = n_{cl}$, the LPG

resonance dip disappears. The reason is that the core will see an infinitely thick cladding region and without the cladding-surrounding interface, there is an absence of guided region and thus the cladding modes cease to exist [65, 68, 69]. In this situation where $n_{ext} = n_{cl}$, the cladding modes will be converted to radiation modes due to the lack of total internal reflection at the cladding-surrounding interface, resulting in a diminutive loss in the transmission spectrum [65, 68, 69].

Another interesting phenomenon appears in the LPG transmission spectrum as the external medium refractive index increases above that of the cladding. Figure 2.21 depicts the reappearance of the LPG transmission dip and a slight right shift in the spectral location, which is due to the difference in the nature of Fresnel and total internal reflections. Duhem and co-workers [69] suggested that due to a discontinuity of the indices between the cladding and the external medium, the radiation modes ceased to exist. With this discontinuity, a part of the cladding mode energy is reflected at the cladding-surrounding interface. This ratio of reflection is dependent on the Fresnel coefficients, which is dependent on the external medium refractive index. Hence the cladding modes that exist in the cladding region will be depicted as attenuated cladding modes or leaky modes because of the absence of total internal reflection but rather Fresnel reflection occurring at the cladding-surrounding interface [69]. In this case, lacking a confining structure to contain the cladding mode within the cladding region, the phase-matching condition is no longer valid.

At higher refractive index, the external medium and the cladding form a discontinuity at this interface, which means the cladding is no longer infinite and the radiation mode description becomes invalid. As mentioned earlier, that at the cladding-

surrounding interface, the Fresnel reflection coefficients is dependent on the external medium refractive index. For a higher external medium index, the portion of energy reflected of the attenuated cladding modes will be higher. These attenuated cladding modes are only able to be guided by the abrupt cladding-surrounding discontinuity if they succeed at being continually amplified down the length of the cladding in the direction of propagation. The difference between the guided cladding modes and the guided attenuated cladding modes is that the latter's resonance wavelength do not shift with the value of the external medium refractive index due to the lack of optical confinement by the external medium.

The effect on the LPG transmission spectrum at different external medium indices is a change of depth of the resonance dip. It can be observed from fig. 2.21 that when the external medium index increases from 1.4601 to 1.6716, the depth of the LPG resonance dip increases steadily. This is due to the increase in the Fresnel reflection coefficients that yields an improved reflection at the cladding-surrounding interface, resulting in an increase in energy in the attenuated cladding modes. With higher energy attenuated cladding mode, more efficient coupling occurs between guided core mode and the attenuated cladding mode, which explains the increase in depth of the LPG resonance dip with respect to the increase of external medium index beyond that of cladding [69].

In summary, the concept of mode coupling between the fundamental guided core mode and other modes has been discussed through the use of coupled mode theory. The mode coupling between the fundamental mode and other modes form is the key point of operational principle for both FBG and LPG. For total exchange of

energy between two modes, the phase matching condition has to be met. In a LPG, the fundamental forward guiding core mode will be coupled into numerous discrete cladding modes. The cladding modes are dependent on the differential refractive index between the core and cladding effective refractive index and the grating period. This dependency has been discussed using the LPG characteristic curves. Another important parameter to the LPG that has been discussed is the LPG coupling coefficient. The coupling coefficient determines the strength of exchange of power between the fundamental mode and the cladding modes. As the work of this project is on intensity-based LPG sensors, the coupling coefficient plays a significant role in these sensors.

The final portion of this chapter covers how the LPG can be used as a sensor for measuring external perturbations, such as temperature, strain and external refractive index. An interesting phenomenon on the different response the LPG gives when external refractive index lower than that of cladding and higher than that of cladding was also highlighted.

Before proceeding to the different type of intensity-based LPG sensors developed, an overview of different LPG fabrication methods will be discussed in the next chapter.

CHAPTER 3: Fabrication of Long Period Gratings

3.1

INTRODUCTION

This chapter covers various techniques used in the LPG fabrication process. These techniques include the UV-laser amplitude mask [70], the CO₂-laser [71], the femtosecond laser [72], the electric arcing [73] and the corrugated etching techniques [74]. Discussion will also include problems encountered during the LPG fabrication process when using the hydrogen-loaded standard single mode fiber (SMF).

3.2

FABRICATION TECHNIQUES

There are several techniques, which have been employed in the fabrication of long period gratings. The techniques that will be presented in this section include the amplitude mask technique, the CO₂ laser technique, the femtosecond pulse laser technique, the electric arc technique and the corrugated etching technique.

3.2.1 UV-LASER AMPLITUDE MASK TECHNIQUE

UV-laser amplitude mask technique has been the most popular technique used for the fabrication of long period gratings. In fact this is the main technique used in this project. In using this fabrication technique, one requirement has to be fulfilled; that is the single mode fiber has to be photosensitive. Photosensitivity is defined as the property of a photo-conductive and electro-optic material to exhibit and retain differential modulation in its refractive index as a result to exposure to spatial distributions of intense electromagnetic radiation [75]. Photosensitivity was first discovered in 1978 at the Canadian Communication Research Center by Ken Hill and his co-workers [76], leading to the birth of fiber Bragg gratings.

Several techniques can be used to enhance photosensitivity in a SMF, such as hydrogen loading [77], Germanosilicate fiber co-doped with boron [78], flame brushing [79] and strain application [80]. Two most commonly used photosensitive fibers are the hydrogen- or H_2 -loaded fiber and germanosilicate fiber co-doped with boron or B/Ge co-doped fiber. H_2 -loaded fiber is less costly and more photosensitive than B/Ge co-doped fiber. The advantage of using B/Ge co-doped fiber for fabricating an LPG is its smaller resonance wavelength drift after laser inscription as compared to an LPG fabricated with H_2 -loaded fiber. The higher resonance wavelength drift in H_2 -loaded fiber is due to the out-diffusion of H_2 molecules immediately after inscription. This problem will be discussed at a later part of this chapter.

The fabrication setup using UV-laser amplitude mask technique is shown in figure 3.1.

Figure 3.1 Setup configuration of amplitude mask technique for the fabrication of long period gratings.

Amplitude masks with a rectangular transmittance function are imprinted on chrome-plated glass and have a $100 \text{ mJ/cm}^2/\text{pulse}$ optical threshold damage level [40]. The duty cycle of the rectangular function is 50 % and length of the mask varied from

1 cm to 5 cm. Either pulsed 248 nm KrF excimer laser or 248 nm continuous wave frequency doubled argon-ion laser can be used as the irradiation source. The portion of the photosensitive fiber to be UV illuminated is stripped off the acrylic jacket, in which the length to be stripped off is dependent on the intended grating length to be fabricated. The reason for the removal of the acrylic jacket is that acrylic absorbs UV and will prevent the UV light from penetrating into the fiber core if it is not removed. The stripped fiber will then be placed in front of the amplitude mask, as shown in figure 3.1. The fiber was supported on both sides of the bare region to prevent bending of the optical fiber. Light from a LED source, with a wavelength range between 1520 nm to 1620 nm, is launched from one end of the fiber while an Optical Spectrum Analyzer or OSA is connected on the other end to monitor the growth of the LPG during UV illumination.

Figure 3.2 Evolution of a typical long period grating using an amplitude mask on UV exposure; curves A to E represent the transmission spectrum in one-minute intervals after the exposure was initiated [40].

Figure 3.2 depicts the increase of the long period grating resonance dip at the highest wavelength within the spectral range of the optical source. As observed, the resonance dip shifted towards the longer wavelength side while the peak loss increases

as the UV illumination is continued. The spectral shift can be attributed to the increase in the guided mode effective refractive index while the isolation grows due to enhancement in the coupling coefficient. This shift of the resonance dip during the writing process is a function of the order of the corresponding cladding mode, in which the coupling to different cladding modes is clearly evident in the grating transmission spectrum, as shown in figure 3.3. The typical wavelength shift of highest order cladding mode during fabrication process can range from 40 nm to 100 nm. Additional observation from figure 3.3 shows that each resonance dip has a different peak loss due to distinct coupling coefficients for the corresponding cladding modes.

Figure 3.3 Transmission spectrum of a long period grating with a period of $\Lambda=450\mu\text{m}$. The discrete spiky loss dips corresponds to the coupling of the fundamental core mode to discrete cladding modes.

The UV illumination stops when the complete power transfer condition is satisfied for the resonance dip with the longest coupling wavelength in the optical spectrum of the LED. In other words, the peak loss of the resonance dip reaches its maximum. If the UV illumination does not stop after achieving maximum peak loss, the peak loss will start to decrease, resulting in a reduction of the resonance dip. Experimentally it was found that the duration of the fabrication process ranges from 5 minutes to 20 minutes depending on the type of photosensitive fiber used. A point to note is that if hydrogen loaded photosensitive fiber is used, the duration of the UV illumination will increase with the increased period of the storage of the hydrogen-loaded fiber, after the hydrogen loading process. This is due to the out-diffusion of the hydrogen atom from the fiber, during storage, making it less photosensitive.

A major advantage of amplitude mask technique is that a number of long period gratings with the same grating period can be fabricated simultaneously. This can be accomplished by placing more than one single fiber in front of the amplitude mask, as shown in figure 3.4.

Figure 3.4 Setup for batch fabrication of long period grating just by using a single amplitude mask.

Although only one fiber is monitored during the writing process, if the transverse profile of the UV radiation is assumed invariant, all gratings in the batch is expected to have similar transmission spectra.

3.2.2 CO₂ LASER TECHNIQUE

An alternative technique for the fabrication of long period grating is to use CO₂ laser, which is a non-photochemical process as compared to UV-laser technique. Davis and co-workers first demonstrated this technique of using CO₂ laser to fabricate LPG in 1998 [71]. In their experiment, a computer-controlled mechanical stage with a translation accuracy of 0.1 μm pulls the fiber through a fixture so that it would be in alignment with the 145 μm Gaussian focal spot of the CO₂ laser beam. The power in the focused beam was 0.4 W. A 3.9 g weight was attached to the fiber over a pulley to provide a constant tension. As the fiber was moved to each new position by the translation stage, the computer opens a shutter for a programmed pulse duration allowing the CO₂ beam to be incident on the fiber. During this fabrication process, the spectral transmission of the fiber was monitored using a spectrum analyzer and a broadband source covering the range from 1450 nm to 1600 nm. A camera mounted over the fiber provides visual verification that energy flux is sufficiently low so that no physical deformation of the fiber would occur. After fabrication, for a greater dynamic range, the grating transmission was characterized using a tunable laser source and a power meter.

With the present cost of a CO₂ laser system reduced drastically and the flexibility of fabricating long period grating on standard non-photosensitive optical fiber, this technique has gained popularity. In the amplitude mask technique, which

requires a UV laser, photosensitive fiber is required in the fabrication of the LPG. In the CO₂ laser technique, non-photosensitive fiber can be used for fabricating long period grating as this technique is based on thermal shock and not based on the bleaching of germanium–oxygen-deficient center or GODC band. The wavelength of the CO₂ laser, which is 10.6 μm , is highly absorbed by the silica fiber, and converted to heat in the fiber. The heated portion then experiences stress relief and densification in the fiber, leading to a change in refractive index in the fiber [71]. Another reason that leads to the popularity of this technique is that no amplitude mask is required during the fabrication process. In the Amplitude Mask technique, the grating period in the LPG is dependent on the slit period of the amplitude mask. This results in some inflexibility as one has to change the amplitude mask if another LPG of different grating period is required. CO₂ laser technique does not require amplitude mask as the refractive index modulation along the fiber is created a point at a time.

Figure 3.5 Schematic layout of the LPG fabrication system using CO₂ laser technique.

In the LPG fabrication system using the CO₂ laser technique, as shown in figure 3.5, the beam from the CO₂ laser will be focused onto the optical fiber through an objective lens. A computer was programmed to control the shutter, which is located

inside the CO₂ laser. When the shutter is opened, the CO₂ laser will lase onto the bare fiber. A mirror and an objective will be mounted on the translation stage to provide lateral scanning of the laser beam on the bare fiber. During the fabrication process, the translation stage will move by distances matching that of the required grating period and the shutter will open and close accordingly. With the combination of shutter control and lateral motion control, the user is able to fabricate LPG of different grating periods. Depending on the design and input parameters into the computer, a non-uniform or chirp grating can be fabricated using this system.

One characteristic of an LPG fabricated via the CO₂ laser technique is that the refractive index change across the entire cross-section of the fiber is asymmetric. The reason is that when the CO₂ laser beam is focused on the fiber, both transmission and reflection occurs on the incident side of the fiber simultaneously. As silica glass has strong absorption around the wavelength of the CO₂ laser, the CO₂ light intensity incident on the exit side of the fiber (figure 3.6) is weaker than the light incident on the front side of the fiber. This results in an asymmetric index change across the entire cross-section of the fiber with the refractive index change on the incident side being larger than that on the escape side [81].

Figure 3.6 Schematic diagram of optical power distribution on cross-section of a single-mode optical fiber.

One problem associated with LPG fabricated using CO₂ laser is the induced azimuthally asymmetric refractive-index change in the fiber cladding due to one-sided exposure. The same cladding mode propagating in the cladding region will experience different refractive index at different cross-sectional cladding region. This can pose polarization-dependent loss (PDL) problem when it is used for optical communication applications, such as making of gain-flattened erbium-doped fiber amplifiers [82]. However, as highlighted in the review of chapter 1, with the correct fiber axial orientation, the CO₂ fabricated LPG can be used as intensity-based bending sensor. For the LPG fabricated using UV-lasers, the refractive index changes primarily in the optical fiber core. Although using UV-laser method does induce birefringence [83], the PDL is small as the refractive index change in the fiber core is relatively uniform as discussed by G.D. VanWiggeren *et. al* [81]. A comparison shows that the CO₂-induced LPG has a PDL of 1.2dB and the UV-induced LPG has a PDL of 0.2dB [84]. Despite its drawback, CO₂ fabricated LPG finds its way into numerous applications both in communication [85] and optical sensing [86].

Long-period gratings fabricated by exposure to CO₂ laser pulses have been shown to be exceptionally stable. Band rejection characteristics are unchanged in resonant strength and wavelength even when subjected to temperatures up to 1200 °C. These long-period gratings are essentially permanent. Corresponding UV- induced gratings, on the other hand, would be erased in seconds at these high temperatures. Thus CO₂ laser-induced long-period gratings are excellent candidates for both long-lifetime and high-temperature applications.

3.2.3 FEMTOSECOND LASER PULSE TECHNIQUE

Amplitude mask technique through UV-light illumination is the most commonly used technique during the LPG fabrication process. However, LPG fabricated using this technique has a problem with stability over time as the index change relaxes even below 100 °C. In addition, since UV-light illumination is used for its fabrication, photosensitive fibers will have to be used.

In 1999, Yuki Kondo and co-workers reported a novel technique for fabricating LPG using focused irradiation of an infrared femtosecond laser [72]. In this technique, a periodic structure of the refractive index was induced in the core of a single-mode fiber using femtosecond laser which the focused irradiation is believed to have caused a densification of the glass resulting in the index change of the fiber core where the laser is focused in. In addition, a non-linear reaction through a multiphoton process and conventional heating by a multiphoton transition can occur during laser irradiation [72].

Figure 3.7 Experimental setup of the LPG fabrication system using infrared femtosecond laser [72].

The experimental set-up for the fabrication technique is shown in figure 3.7. The most important advantage is that the LPGs fabricated using this technique have high resistance to thermal decay below 500 °C, which shows that they have superior aging characteristic. Since thermal degradation of long-period gratings fabricated using UV light irradiation occurs even at temperatures below 100 °C, annealing of the grating at an elevated temperature for a short time, thereby removing the unstable part of the UV-induced index, is required for the thermal stability of grating performance. On the other hand, the LPGs fabricated by focused irradiation of femtosecond laser pulses have thermal stability since the cause of the index increase induced by the focused irradiation of femtosecond pulses is different from that of the UV-induced index increase. In UV-induced gratings using Ge-doped silica glass, photo-excitation of oxygen-vacancy-defect states forms paramagnetic GeE' centers, which contribute to the refractive index change [72]. The defects related to GeE' centers relax even at temperatures below 100 °C and hence the grating performance degrades thermally. Compared with LPGs fabricated using UV light irradiation, those fabricated by focused irradiation of femtosecond laser pulses have a higher temperature resistance and a superior aging characteristic. This technique does come with its drawbacks such as the requirement of expensive femtosecond laser and the asymmetric refractive index induced across the cross-section of the fiber. Like the LPG fabricated using CO₂ technique, which is a non-photochemical process, LPG fabricated using the femtosecond laser has the similar modal birefringence in the fiber cladding as that of the cladding in CO₂ fabricated LPG. Hence the LPG fabricated using femtosecond laser has higher PDL comparing to LPG fabricated using UV-laser [87].

3.2.4 ELECTRIC ARC TECHNIQUE

A common way for connecting two bare optical fibers together is by fusion arc splicing. G. Rego and co-workers demonstrated the technique of LPG fabrication using electric arc technique [73]. Electric arc technique is similar to CO₂ laser technique in that local heating of the fiber takes place in the process of grating inscription by an electric arc discharge. Electric arc fabricated LPG also has comparable thermal stability results with LPG fabricated with CO₂ laser. The main advantage of electric arc technique is its simplicity as compared to the rest of the techniques mentioned above, which requires the use of expensive laser equipment. Using this technique, LPG can be fabricated using any type of optical fiber, because their spectral characteristics will mainly be defined by the intrinsic properties of the silica glass itself.

Figure 3.8 Schematic diagram of the experimental setup of electric arc fabrication system for the fabrication of LPG.

Figure 3.8 illustrates the experimental setup of the electric arc fabrication system. The setup and fabrication process is similar to that of the CO₂ laser technique. The bare fiber is clamped between two fiber holders so that the fiber will be kept straight throughout the process. The fiber holders are mounted on a translation stage,

with a 0.1 μm resolution, with the stage providing the lateral movement required. Instead of a CO_2 laser source, a pair of electrical probe was used to produce the electric arc discharge.

The reason for the induced refractive index change in the region of the fiber exposed to electric arc can be explained by the fast local heating-cooling process [73]. The fast local heating-cooling process anneals periodically residual stress in the fiber region, which is exposed to electric arc, and creates new stress in the fiber. This will result in a change in the glass density of the exposed region of the fiber and hence a change in refractive index.

G. Rego also found that the LPG fabricated by electric arc technique exhibits good thermal stability. The LPGs are able to operate linearly up to a temperature of 800 $^{\circ}\text{C}$ without any irreversible degradation of their spectra. With such simple and low cost fabrication technique and good thermal stability, LPGs fabricated by this technique provide a good potential to be used as disposable sensors in high temperature environments.

3.2.5 CORRUGATED ETCHING TECHNIQUE

Lin and Wang [74] described a new type of long-period grating made of a corrugated structure over which periodical strain distributions are induced when external torsion or tensile force is applied. It is also shown that such a corrugated long-period grating can serve as a loss tunable band-rejection filter by adjusting the amount of the applied tensile strain. Figure 3.9 illustrates the schematic diagram of a corrugated LPG.

Figure 3.9 Schematic diagram of a corrugated LPG [74].

The corrugated LPG consists of two regions. First region is the region with the cladding etched to a diameter $D1$. The other region is the unetched region with a diameter $D2$. When a tensile force is applied along the fiber in an equilibrium condition, each of the two regions will experience different tensile strain that is inversely proportional to the cross-sectional area of the corresponding region. Therefore, by photoelastic effect, the differential strain results in periodic index modulation. From previous chapter, the coupling strength of the gratings in an LPG is,

$$S = \sin^2(\kappa L) \quad (3.1)$$

where κ is the coupling coefficient and L is the length of the corrugated LPG. Hence the resonant dip can be tuned by the applied tensile force. The peak resonance wavelength at which coupling occurs is governed by the following equation,

$$\lambda = \lambda_{res} \left[1 + \frac{(\delta n_{core} - \delta n_{clad}) \left(\frac{d\lambda_{res}}{d\Lambda} \right)}{(n_{core} - n_{clad})^2} \right] \quad (3.2)$$

where λ_{res} is the initial resonant wavelength, n_{core} and n_{clad} are effective indices of fundamental core and cladding modes respectively, Λ is the grating period, and δn_{core} and δn_{clad} are the index changes in the core and cladding region respectively. For the corrugated long-period grating, since the Young's modulus is nearly uniform in the cross-section of a fiber, the resultant tensile strain is not a strong function of the cross-section. As a result, the index changes induced in both core and cladding over the entire cross-section in the long-period grating are similar. From equation 3.2, the difference $(\delta n_{core} - \delta n_{clad})$ as induced in a corrugated long-period grating is much smaller than δn_{core} as induced in a conventional long-period grating, which may result in much less wavelength shifting in the corrugated long-period grating.

The experiment is arranged as follows: a dispersion-shifted fiber with an original cladding radius of 62.5 μm is used. The corrugated structure was built by etching a pre-patterned fiber using a hydrofluoric acid solution. It has a length of 20 mm with an etched radius of $\sim 20 \mu\text{m}$ and a period of $\sim 400 \mu\text{m}$. A tensile force and an external torsional torque were applied to induce an average tensile strain, dL/L , and an average twisting rate, $\tau = \frac{2\pi N}{L}$ (rad/m), respectively. The dL and N are the total elongation and the number of torsional turns over the distance L between the fixed and stretching points. To facilitate a precise control on the adjustment of τ and dL/L , L is set as long as 1 m owing to the precision limitation of the mechanical stages [74].

The major advantage of this long-period grating is that the tunabilities of wavelength and loss of a corrugated long-period grating are obtained by adjusting the applied torsion and tensile forces respectively, using a simple mechanical set-up. Since

the shift of resonant peak wavelength is very small ($< 2 \text{ nm}$) during the overall loss tuning, a specified resonant peak wavelength and loss can easily be obtained by first adjusting the amounts of torsional and tensile forces. More than 40 nm and 25 dB can be tuned without residual stress [85]. Such a tunable long-period grating is expected to be useful in various applications in optical communications and sensing systems [74, 88].

It can be seen that LPG can be fabricated using numerous techniques. The technique that was used in this project is the amplitude mask technique using a KrF excimer UV laser. It was realized that the fabrication of long period grating using hydrogen-loaded fiber involves higher level of patience and skill as compared to the fabrication of FBG using the phase mask technique. The next section will present the observed phenomenon of the long period grating immediately after the fabrication process.

3.3 PROBLEM WITH HYDROGEN-LOADED LPG

It was mentioned earlier that the most common technique for the fabrication of LPG is the UV-laser illumination amplitude mask technique. All the LPG sensors used in this work were fabricated with hydrogen-loaded optical fiber using the UV-laser illumination amplitude mask technique. Although the use of hydrogen-loaded fiber is more cost effective and induced a greater refractive index change when compared to B-Ge co-doped fiber, it was observed that the LPG spectrum is unstable immediately after the fabrication process.

Figure 3.10 Diagrams show the continual growth of the LPG with the grating period of 450 μm spectrum immediately after UV-laser illumination has stopped. (a) spectrum immediately after the UV-laser is switched off. (b) spectrum after 2 mins. (c) spectrum after 4 mins. (d) spectrum after 6 mins.

Figure 3.10 depicts the development of the LPG, with the grating period of 450 μm , transmission spectrum minutes after the lasing of UV-laser had stopped. Observations from the figure show that the LPG resonance wavelength continued to shift towards the longer wavelength side after the UV-laser illumination. In addition to

the wavelength shift, the coupling strength of the grating continued to increase for the first 4mins and decreased beyond that. Figure 3.11 depicts the shift of resonance wavelength with respect to time, (figure 3.11a), and growth of the resonance dip with respect to time, (figure 3.11b), respectively.

Figure 3.11 (a) Shift of resonance wavelength with time after UV-laser illumination.
(b) Growth of resonance dip with time after UV-laser illumination.

From the plot in figure 3.11, the resonance wavelength shifted linearly with time, while the resonance dip increased for the first 5mins and then decreased after that. The reasons for the observed phenomenon can be due to the diffusion of hydrogen in the core and the cladding in the fiber [89].

After UV-laser illumination, there are clearly defined sections of the hydrogen-loaded fiber that were exposed and unexposed to the UV laser during the inscription of the LPGs, see figure 3.12.

Figure 3.12 The diagram shows a section of the hydrogen-loaded fiber exposed and unexposed the UV-laser illumination during LPG fabrication.

The hydrogen concentration in the exposed core section was much less than that in the unexposed core section since most of the hydrogen atoms were involved in the reaction that caused the change in refractive index. In addition, the large increase in temperature, because of UV absorption in the core of the fiber, also accelerated the diffusion of hydrogen out of the exposed region. Therefore, this resulted in a large difference in hydrogen concentration between the exposed core region and the unexposed core section and between exposed the core section and the exposed cladding region immediately after UV-laser illumination.

In order to maintain equilibrium, the hydrogen will diffuse from both the unexposed core region and the cladding region to the exposed core region as well as into its surroundings. Since refractive index of the fiber is a function of the hydrogen concentration [90], the increase in hydrogen concentration in the exposed core region due to diffusion will lead to an increase in the refractive index. This will lead to an increase in the amplitude index modulation in the coupling coefficient (equation 3.1)

and hence an increase in the coupling strength of the grating. This explains the increase of the resonance dip for the first 5 minutes after the fabrication process, as shown in fig. 3.11(b). The increase in the amplitude index modulation also meant an increase in the effective refractive index of the core, n_{core}^{eff} . In addition, since most of the reaction has taken place in the core of the fiber, as the germanium defects in the cladding region is negligible, the change in the refractive index in the cladding region is negligible and therefore the effective refractive index of the cladding, $n_{cladd,m}^{eff}$ can be assumed to be unchanged. Hence from the phase matching equation, $\lambda = (n_{core}^{eff} - n_{cladd,m}^{eff})\Lambda$, there will be an increase in the resonance wavelength. This explained the observed shift of the resonance wavelength towards longer wavelength minutes after UV-laser illumination stopped, figure 3.11(a).

This phenomenon can pose potential problem, as it will be difficult to fabricate LPGs with the desired characteristics. Even if an engineer or researcher knows the trend, it applies only during that time of fabrication. Due to the diffusion of hydrogen out of the hydrogen-loaded fiber, even if the latter is kept at very low temperature, the trend of the change of resonance wavelength and resonance dip immediately after UV-laser illumination may be different. One method of stabilizing the LPG spectrum after fabrication is by heat-annealing and UV pre-exposure [91], which is done before the actual LPG fabrication step. In this method, before the writing of LPG, the hydrogen-loaded optical fiber is first pre-exposed to a uniform intensity UV-laser source. The pre-exposed optical fiber is then annealed to force the entire hydrogen molecules to diffuse out of the fiber before the writing of LPG commences. Through pre-exposure, the hydrogen-loading effect and hence the photosensitivity is preserved. Through annealing, the removal of hydrogen molecules will help to reduce the LPG resonance

wavelength shift. This is because of the non-existence of hydrogen molecules to drift from the unexposed region to the exposed region in the fiber core after LPG fabrication, which will cause changes in the induced refractive index. Using this method, Hiroyuki Kawano and co-workers [91] found that the LPG resonance wavelength and transmission dip after the completion of the LPG writing process is more stable than with the typical procedure without UV pre-exposure.

3.4 ANNEALING OF LONG PERIOD GRATING

Despite continuous change in the LPG spectrum immediately after fabrication, this change will be reduced over time. This happens when the hydrogen concentration in the fiber reaches a state of equilibrium [89]. At equilibrium, the hydrogen concentration will be uniform throughout the fiber but still larger than that in the atmosphere. Thus this concentration imbalance will cause the hydrogen to diffuse out from the fiber into the atmosphere. The diffusion of the hydrogen out of the fiber will then reduce the average refractive index in the core and the cladding and forces the resonance band to move back to the lower wavelength [89]. The process of hydrogen diffusing out of the fiber at room temperature is very slow and usually takes hundreds of hours to complete. A prolonged waiting time will not be economical and feasible during commercial production of LPGs.

To accelerate this process of hydrogen diffusion out of the fiber completely in a matter of a few hours, the fiber, with LPG written on it, has to be placed in an oven and annealed at a high temperature immediately after fabrication. Results have shown the effect of annealing LPG at a temperature of 150°C that the resonance wavelengths stabilized to their final values after a few hours, figure 3.13.

Figure 3.13. Shift of LPG resonance wavelengths due to annealing at temperature of 150°C [40].

There is another reason for annealing the LPG. As the LPGs are used as components in systems, be it communication systems or sensor systems, it might be required to operate at temperatures higher than room temperature. In some cases, where a LPG is used as sensor in an engine for example, the working temperature may be above 100 °C. Ergodan and co-workers [92] had shown that for FBG written in germanium-doped fiber, a portion of the UV-laser-induced refractive index change was unstable and decayed over time depending on the operating temperature. This instability arises from the subtle reduction in the concentration of index-raising defect sites.

In an LPG, this decay of a part of the induced refractive index modulation will cause the resonance wavelength to shift further into the shorter wavelength. In addition, the coupling strength of the grating will be reduced. For example, the resonance wavelength of a LPG with maximum coupling strength or resonance dip will reduce with time, resulting in a weaker coupling strength or a shallower dip. Therefore it is important that such unstable defects are removed from the grating prior to use and annealing of the LPG helps to remove these defects. The annealing

temperature for the LPG has to be higher than the temperature in which the LPG will be operating at in the system. Hence annealing the LPG serves two main purposes – removal of residual hydrogen and removal of unstable UV sites in the grating.

For this work, the LPGs were annealed at 80 °C to 100 °C and over duration of 12 hrs. It was observed that after annealing, the LPGs resonance wavelengths had shifted to the shorter wavelength side. This is attributed to the removal of hydrogen and UV sites which will then cause the reduction of the effective refractive index in the core of the fiber, as predicted using the phase matching equation, $\lambda = (n_{core}^{eff} - n_{cladd,m}^{eff})\Lambda$. In addition to wavelength shift, the coupling strength will be reduced as well. The experimental results plotting the LPG spectra before and after annealing is shown in figure 3.14.

Figure 3.14 Transmission spectrum of a 320µm LPG (a) before annealing, (b) after annealing at 100°C for 20hrs.

The shift of the resonance wavelength and the change in the coupling strength of the LPG is dependent on the annealing temperature and duration. An LPG with the desired resonance wavelength of coupling strength can be tuned by controlling the

annealing temperature for a fixed duration. This technique has been applied for tuning the resonance wavelength of a 475 μm period LPG to the wavelength region around 1530 nm for use as EDFA gain equalizer. The result of this will be presented in the later chapter.

Care has to be taken if an LPG is to be fabricated to yield the maximum coupling strength or resonance dip. As the change in the coupling strength follows a sine function (equation 3.1), the coupling strength can also decrease through annealing. Hence, the LPG will have to be over coupled such that $\kappa L > \frac{\pi}{2}$ during the fabrication phase. This is to ensure a higher probability of achieving LPG with high coupling strength after annealing.

From the discussion, numerous LPG fabrication techniques have been presented in this chapter. They are UV-laser amplitude mask technique, technique using CO₂ laser, femtosecond pulse laser technique and corrugated etching technique. The most common technique used today is the UV-laser amplitude mask technique, which is also the same technique used to fabricate the LPG used for this project.

In addition to the fabrication techniques, the problem experienced pertaining to the stability of LPG using H₂-loaded optical fiber after fabrication was also highlighted and presented. One recommended method of stabilizing the LPG spectrum after fabrication is by UV pre-exposure method. In the last part of this chapter, it was discussed that to achieve long term spectrum stability, it is recommended that the LPG has to go through annealing at 100 °C immediately after the fabrication process. Starting from next chapter onwards, the focus will be on the results and discussions on the two

novel LPG-based intensity sensors that were developed and characterized. The two novel LPG-based intensity sensors developed are the embedded LPG bending sensor and the gelatin-coated LPG high relative humidity sensor.

CHAPTER 4: Application of Embedded Long Period Gratings (ELPG) as Bending Sensor

4.1

INTRODUCTION

A novel embedded LPG or ELPG bending sensor will be presented in this chapter. In the ELPG, the material used for embedding LPG is carbon-fiber composite. The work focuses mainly on two main portions; the response of the ELPG to bending and the performance characteristics of the ELPG sensor. Further from the experimental results, it was shown that a single ELPG can be used for both detecting and measuring bending and bend direction.

There will be three parts pertaining to this section. Experimental setup will be covered in the first part. The second portion will focus on the ELPG sensor experimental results and discussions. The last section of this chapter will discuss the issue of temperature effect on the ELPG sensor. Matrix inversion method was employed for measuring bending curvatures and temperature simultaneously.

4.2

EXPERIMENTAL SETUP

In an embedded LPG bending sensor, the LPG is embedded in between layers of carbon-fiber composite laminate. This section will discuss on the carbon-fiber composite laminate and the procedures for the embedding process. The experimental setup for the bending test will also be covered here.

4.2.1 CARBON-FIBER COMPOSITE

Carbon fiber composites have good structural properties. Carbon fiber composites are ten times stronger than steel, yet are still five times lighter. Carbon fiber composites have superior fatigue properties to all known metallic structures, and

when coupled with the proper resins, carbon fiber composites are one of the most corrosion resistant materials available. Carbon fiber has found wide application in commercial and military aircraft, recreational, industrial, and transportation markets. Carbon fiber composites are ideally suited to applications where strength, stiffness, lower weight, and outstanding fatigue characteristics are critical requirements. They are also used in the situations where high temperature, chemical inertness and high damping are important. Although carbon fiber composite has numerous advantages, there are a few points of considerations when selecting the carbon fiber composite as the embedding material. The points are described as follows:

a. **SENSITIVITY**

Sensitivity expresses the response of the system to an input stimulus. When sensing is through an optical fiber that is embedded in a material, it will be considered as indirect sensing. The reason is that the fiber does not experience the external perturbation directly but rather measure the deformation of the embedding material and the results are then correlated to external perturbation. The choice of embedding material plays an important role as the embedding material must have the capability to transfer the external perturbation, acting on the material, into a change in the property of the optical fiber.

b. **DYNAMIC RANGE (LINEAR SENSING RANGE)**

Dynamic range indicates the margin of value of the input or measurand that the sensor can measure. It is the span between the maximum and the minimum values of the measurand that can be measured by the sensor. Most embedded sensors will reach the elastic limit where permanent deformation will occur and the output of

the sensor then becomes nonlinear. Hence it is important that the operating region of the sensor falls on the elastic or linear region for linear and reproducible results.

From previous work [93], it has been demonstrated that using carbon-fiber composite material as the embedding material enables the embedded FBG sensor to achieve greater stability, linear results and wider sensing range. Carbon-fiber composite offers good mechanical performance such as high tensile strength, lightweight and resistance to environmental corrosion. This offers protection to the optical fiber which is critical in industrial applications and applications working in harsh environmental conditions [94]. An important feature of the carbon-fiber composite is that they remain elastic until total deformation [95]. From a strain test conducted, by applying force orthogonal or perpendicular to the axis of the optical fiber, to bare and embedded FBGs, as shown in figure 4.1 and figure 4.2, it was shown that the sensing dynamic range is enhanced in the case of the embedded FBG [93].

Figure 4.1 Non-linear axial stain versus force applied to bare FBG [93].

Figure 4.2 Linear axial strain versus force applied to embedded FBG [93].

In this project, the carbon-fiber composite, Hexcel Hexply[®] 913, used as the LPG embedding material. HexPly[®] 913 exhibits outstanding environmental resistance, whilst retaining good hot/wet mechanical performance. Owing to its low thermal expansion coefficient, $-0.1 \times 10^{-6} / ^\circ\text{C}$, the carbon-fiber composite has a lower thermal expansion coefficient as compared to that of an optical fiber, which has a thermal expansion coefficient of $6.3 \times 10^{-6} / ^\circ\text{C}$. The carbon-fiber composite helps in reducing the LPG spectrum's sensitivity to temperature fluctuations.

4.2.2 EMBEDDING PROCESS

The LPG used in the experiment was fabricated using amplitude mask technique on a photosensitive single mode fiber. The fabricated length of the grating is 5 cm. In order to achieve photosensitivity, standard telecommunication optical fiber (SMF-28) was hydrogen-loaded in the hydrogen chamber under a pressure of 1500 psi for a week. To assist in the diffusion process of H_2 into the optical fiber, the temperature of the chamber was heated up to 70°C . Through an amplitude mask of

450 μm periodicity, the hydrogen-loaded fiber was irradiated using KrF excimer laser at a wavelength of 248 nm and energy of 300 mJ. In this experiment, the LPG was fabricated with the cladding mode having the highest wavelength attenuation band within the optical communication window of 1520 nm to 1620 nm. Growth of the LPG was monitored throughout the fabrication process using an optical spectrum analyzer (OSA, Ando AQ6317) and a tunable laser source (TLS, Ando AQ4321D). To stabilize the grating, the LPG was annealed at 85 °C for 6 hrs, and after that the LPG was ready for embedding.

A carbon-fiber composite laminate is made up of layers of carbon-fiber composite prepreg stacked on top of one another. A prepreg consists of a combination of a matrix (resin or epoxy) and carbon-fiber reinforcement. The role of the matrix is to support the fibers and bond them together in the composite material. It transfers any applied loads to the fibers and keeps the fibers in their position and chosen orientation. The matrix also gives the composite environmental resistance and determines the maximum service temperature of a prepreg. The fiber reinforcement can come in either unidirectional-reinforcement or fabric-reinforcement, as shown in figure 4.3.

Figure 4.3 Carbon-fiber composite prepeg comes in either unidirectional-reinforcement or fabric-reinforcement [96].

Unidirectional reinforcement carbon-fiber composite prepeg has the highest strength along the direction of the carbon fiber as compared with the fabric reinforcement configuration. In addition, embedding the LPG in a fabric-reinforcement prepeg will not yield a uniform force distribution along the gratings as carbon-fiber orthogonal to the optical fiber will create multiple point stresses on the latter. This phenomenon has been found in the case of FBG embedded in carbon-fiber composite in which the latter is orthogonal to the fiber axis [97]. Thus the LPG will be embedded in unidirectional-reinforcement prepeg.

Before the embedding process, structural design of the carbon-fiber laminate was first performed. A common design used will be the rectangular shaped laminate, as shown in figure 4.4. Commercial software, JL analyzer (AutoFEA Engineering Software Technology Inc), was used to simulate the longitudinal stress distribution along both the rectangular and trapezoidal design laminate when a perpendicular force

was applied at the center of the laminate. The results are shown in figure 4.4 and figure 4.5.

Figure 4.4 Simulated longitudinal stress distribution along a rectangular structure.

Figure 4.5 Simulated longitudinal stress distribution along a trapezoidal structure.

The red region in both figure 4.4 and figure 4.5 is the area under tension. Simulated results show that when bending is applied at the center of the structure the stress is more widely distributed along the center region of the trapezoidal laminate than a rectangular structured laminate. Since the LPG is embedded at the center region of the trapezoidal laminate, the LPG will experience a more uniform stress. Non-

uniform stress across the LPG causes the gratings to chirp, causing a reduction in the resonance dip and ripples in the other areas away from the resonance dip [98]. Although it has potential application as dispersion compensator, for the case of bending sensor, it creates uncertainty in the output readings. Therefore to minimize the probability of occurrence of chirping in the LPG, trapezoidal laminate is chosen.

The embedding process involves 4 main steps, namely thawing and cutting of prepeg, preparation of the curing plates, manual stack-up of the prepegs and curing of the carbon-fiber composite laminate [97]. Description of these processes is presented below;

1. THAWING AND CUTTING OF PREPEGS

This process involves first removing the carbon-fiber composite prepeg from the freezer and allowing it to thaw overnight before cutting it to the required design and size. This is to minimize the risk of trapping water molecules between the layers of prepeg, during the stacking process, which will degrade the strength, durability and sensitivity of the embedded sensor.

2. PREPARATIONS OF CURING PLATE

An aluminum curing plate pair was used as a base for the stack-up of prepeg. This plate was wrapped with a layer of release fabric Teflon coated fiberglass or non-porous release film (Release Ease 234 TFNP) and then cleaned with Isopropyl alcohol (IPA) before stacking layers of prepeg on it.

3. MANUAL STACK-UP OF PREPEGS

The carbon-fiber composite laminate was prepared by stacking layers of prepeg on top of one another, as shown in figure 4.6.

Figure 4.6 A pictorial presentation of fabrication of carbon-fiber composite laminate through multiple layers stacking of composite prepeg.

The stacking process involves layering individual cut prepeg on top of one another and a metal roller was used to even out the surface of the laminate. In this work, the LPG was embedded between the 3rd and 4th layer of the 7 layers laminate. This configuration for embedding the LPG between the 3rd and 4th layer is called 4-3 configuration. After completion of the stacking, another curing plate, wrapped with a breather cloth (Airwaves Super 10) and a layer of release fabric Teflon coated fiberglass or porous release film (Release Ease 234 TFP), will be placed tightly on top of the laminate. The purpose of the breather cloth is for absorption of the excess resin. The overall setup is shown in figure 4.7, before proceeding to the curing process.

Figure 4.7 Complete preparation setup of the laminate fabrication process before curing.

4. CURING OF CARBON-FIBER COMPOSITE LAMINATE

The whole setup is then transferred to the vacuum oven (Salvis Lab Vacucenter). The purpose of vacuum is to remove air from the prepeg lay-up and to provide a consolidating pressure for oven curing. The curing procedures are as follows:

- Curing temperature and time are set at 120 °C and 60 mins respectively.
- Temperature ramp rate is set at 2 °C/min.
- Cool down to room temperature and remove the carbon-fiber composite laminate.

The prototype version of the ELPG is shown in figure 4.8.

Figure 4.8 Diagram shows a prototype version of the ELPG.

After removing the carbon-fiber composite from the curing plates, the embedded LPG or ELPG spectral response to bending is ready to be investigated. A test jig was designed and manufactured to provide a test platform for the ELPG. The setup is shown in figure 4.9.

Figure 4.9 Experimental setup used for investigation of ELPG spectral response to bending.

A micrometer (Newport SM Series Vernier Micrometers) was used to induce bending on the ELPG. One end of the ELPG was connected to an Optical Spectrum Analyzer or OSA (Ando AQ6317), while the other end was connected to the Tunable Laser Source or TLS (Ando AQ4321D). Readings were taken from the micrometer in steps of 0.25 mm depth, h . The radius R of the arc of ELPG under bending is calculated using the depth reading from the micrometer based on the following expression:

$$R = \frac{\left(\frac{d}{2}\right)^2 + h^2}{2h} \quad (4.1)$$

Thus the curvature C is given by:

$$C = \frac{1}{R} \quad (4.2)$$

Using equation 4.1 and equation, a depth of 0.25 mm yields a curvature of 0.251 m^{-1} . This curvature will be used as a measure for the amount of bending the ELPG undergoes.

4.3

RESULTS AND DISCUSSIONS

Experimental results of this novel technique of bend sensing and measurement by ELPG will be presented in this section. The focus will be on the discussion on the ELPG spectrum response to bending and the characterization of the sensor performance. Characterization is an important process as it determines the usability of the sensor. Hence the characterization will cover the sensor sensitivity, repeatability error, hysteresis, etc.

4.3.1 **RESPONSE OF ELPG TO BENDING**

When the LPG is embedded in the carbon-fiber composite laminate, the LPG is surrounded by an external layer of epoxy which forms the matrix of the carbon fiber composite laminate. Due to the LPG’s sensitivity to the external medium, the position of its resonance wavelength is affected by the epoxy’s refractive index, provided that the latter is lower than that of cladding as presented in chapter 2. In the case where the LPG is surrounded by an external medium with refractive index higher than that of cladding (~1.44462), its spectral response will be different [61]. Experimental investigation of LPG surrounded by optical fluid of different refractive index (Lightspan Application Technology) yielded a right shift of the resonance wavelength away from the original resonance wavelength, when the refractive index of the optical fluid is higher than that of cladding. These experimental results are depicted in figure 4.10.

Figure 4.10 Experimental measurements of the LPG transmission spectrum for different surrounding refractive indexes.

It can be observed from the results in figure 4.10 that when the applied optical fluid's refractive index is lower than that of the cladding, the LPG's resonance wavelength shifted towards shorter wavelength side or blue shift. As the optical fluid's refractive index increases, the amount of blue shift increased. This is accordance to equation 2.23 that as the optical fluid refractive index increases, the effective refractive index of the cladding mode increases and therefore according to equation 2.23, the resonance wavelength reduces. When the optical fluid refractive index matches that of the cladding, the resonance dip disappeared as shown in figure 4.10, which is due to the absence of a guiding regime. Beyond the cladding refractive index, the resonance dip was reproduced and its wavelength shifts to the right of the original resonance wavelength. As shown in figure 4.10, further increase of the optical fluid refractive index will not shift the resonance wavelength but only affects the depth of the LPG resonance dip. This is due to the Fresnel reflection of the cladding mode at the cladding/optical fluid interface, which had been presented in chapter 2.

As the manufacturer for the carbon-fiber composite cannot furnish us with data pertaining to the epoxy refractive index, test has to be carried out to see if the matrix refractive index is higher than that of the cladding. This is important as it determines the response of the ELPG to bending. One method is to use the LPG as a sensor to measure the matrix refractive index if the latter is higher than that of cladding. Individual spectrum of the LPG, with $320\mu\text{m}$ grating period, before embedding, after embedding but before curing and after curing were recorded as shown in figure 4.11, figure 4.12 and figure 4.13 respectively. Experimental results showed that the resonance wavelength of the LPG spectrum for a cured ELPG shifted towards the longer wavelength side as compared to the original resonance wavelength of the same

LPG before embedding, as shown in figure 4.13. This happens when the external medium surrounding the LPG has a refractive index higher than cladding and thus this shows that the refractive index of the matrix is higher than that of cladding.

Fig. 4.11 The diagram shows the spectrum of a 320µm LPG before embedding.

Fig. 4.12 The diagram shows the spectrum of a 320µm embedded LPG before the curing process.

Fig. 4.13 The diagram shows the spectrum of a 320μm embedded LPG after curing process.

Having the matrix's refractive index higher than that of cladding, the cladding mode will not be guided under total internal reflection. Instead the mode will experience Fresnel refraction and Fresnel reflection. In addition, with the reduction of the index difference between the cladding and the external medium, the cladding mode field will no longer be confined to the cladding. More energy will be propagated towards the external medium and thus affecting the coupling strength of the LPG.

The coupling strength that governs the transfer of energy between the core and cladding modes can be expressed as, equation 2.45,

$$C = \sin^2(\kappa^m L) \quad (4.3)$$

where L is the grating length and κ^m is the coupling coefficient given by equation 2.37,

$$\kappa^m = \frac{\pi |A_N|}{\lambda^m} \eta^m \quad (4.4)$$

where A_N are the Fourier coefficients defined in chapter 2 and η^m is the overlap integral defined as, equation 2.37.

$$\eta^m = \frac{\left| \int_0^a \Delta n E_{0l}(r) E_{cl}^m(r) r dr \right|}{\sqrt{\int_0^\infty (E_{0l}(r))^2 r dr \int_0^\infty (E_{cl}^m(r))^2 r dr}} \quad (4.5)$$

where a is the core radius, $E_{0l}(r)$ and $E_{cl}^m(r)$ are the electric field distribution of the fundamental guided mode and the circularly-symmetric cladding mode of order m respectively. η^m is the overlap integral between the fundamental guided mode and the cladding modes in the core region. Equation 4.4 shows that, the coupling coefficient is directly proportional to the index modulation in the core and the overlap integral. Therefore when bending is increased, more energy will be sent to the external medium, which will then be lost through scattering and absorption. The reduction of the energy in the cladding mode will thus reduce the overlap integral between the fundamental core mode and the cladding mode. As a result, the coupling strength of the grating will be reduced.

In addition to the lack of confinement of the cladding mode, bending of the LPG will induce a lateral shift in the modal distribution of the fundamental core mode and the cladding mode. Even if air is the external medium, lateral shift of the modal distribution will exist when the LPG is bent [18]. The lateral shift of the modal distribution will cause the grating coupling strength to be reduced, which is due to the reduction of overlap integral between the core mode and the cladding mode as illustrated in figure 4.14. Thus with the lack of confinement and the lateral shift of the

cladding mode field, a small bending on the ELPG will yield a major change in the coupling strength as shown in figure 4.15.

Fig. 4.14 Graphical illustration of the cladding mode field distribution shows that the field overlap in the fiber core between the cladding mode and core mode is reduced for curved LPG (b) instead of straight LPG (a).

Fig. 4.15 Spectral response of ELPG under different bending curvature shows a change in coupling strength.

Results from figure 4.15 depicted that the resonance coupling strength of the ELPG decreases with increased in the bending curvature while the ELPG's resonance wavelength remains constant. Only the cladding mode with the highest attenuation band within the optical communication window is of interest as it has the deepest resonance dip as compared to the other lower-order modes. Therefore a small change in the resonance dip will be more obvious. In addition, working in the communication window yields the flexibility for the ELPG to use existing and cheaper optical modules, and to be incorporated in any optical communication systems if the need arises.

At 0m^{-1} the resonance dip is at its deepest. On the other hand, as the bending increases, this resonance dip decreases in depth, suggesting a reduction in coupling strength between the fundamental core mode and the cladding mode of the ELPG. It can also be observed from the figure that despite reduction in coupling strength with bending, the resonance wavelength remains relatively constant. This is very different from the reported results from two previous published works [17, 19], despite using the same type of standard single mode fiber.

The constant resonance wavelength, as the sensor is bent (figure 4.15), could be due to two reasons. First, it has been shown that the change in the effective refractive index modulation of the gratings in the fiber core is less than 0.1 % for huge curvature [18] and since the bending curvature in this experiment was not large enough to induce a major change in the effective refractive index modulation, the resonance wavelength of the ELPG spectrum would not be affected. In addition, with the external medium refractive index higher than that of cladding, the phase matching

condition of the LPG will no longer be valid. Any major variation in the refractive index will result only in the change in coupling strength, but not the resonance wavelength [69].

The second reason why the ELPG's resonance wavelength remains constant with bending can be correlated to the bending of the LPG with the angle of tilt of the grating with respect to the normal axis of the fiber. Modeling has shown that bending of LPG has the same effect of having tilted gratings with respect to the normal axis of the fiber [18]. Normal axis of the fiber is referred to the axis across the cross-section of the fiber perpendicular to the direction of propagation of light in the fiber core. In order to achieve a change in resonance wavelength, the tilt angle of the gratings must be of significant value, in other words the bending curvature would be large. In the case of ELPG, the resonance wavelength only shows a significant shift when the bending curvature exceeds 2 m^{-1} and beyond. However at this point, the resonance dip disappeared as the coupling strength was greatly weakened.

Recent development has shown that bare LPG fabricated by CO_2 laser exhibits similar bending characteristics as that of ELPG [35], in which the resonance wavelength remains constant while the depth of the resonance dip changes with bending. This was achieved by writing LPG on bend insensitive fiber. Despite the advantages of reduction in fabrication cost by using CO_2 laser and use of non-photosensitive fiber, there is one drawback. The use of bend insensitive fiber, to achieve a relative constant resonance wavelength in bending, can be expensive and therefore adding cost to the sensor system.

4.3.2 SENSOR PERFORMANCE CHARACTERIZATIONS

For use as a bending sensor, the ELPG performance characteristic will have to be thoroughly investigated. The discussion in this section will focus on the ELPG's performance, such as sensor response, repeatability, hysteresis and stability with time. In addition, we will also look into the effect of temperature variations on the sensor's output. Matrix inversion method was used to extract both temperature and bending curvature simultaneously.

4.3.2.1 SENSOR RESPONSE

To minimize the effect of temperature variation on the ELPG, the experiment was carried out in the laboratory with temperature maintained constant at approximately 22.5 °C. As the LPG was embedded between the 3rd and 4th layer of the 7 layers laminate, bending tests were performed on both sides of the ELPG in order to investigate if there are differences in the LPG's spectral response. In the first bending test, the 3-layer side of the ELPG was positioned facing upwards, directly below the micrometer (figure 4.9). Readings from the OSA was recorded at each bending curvature in steps of 0.251 m⁻¹. Figure 4.16 plots the values of the ELPG transmission dip obtained from the OSA for different bending curvatures. The absolute values in the previous sentence refer to the direct readings obtained from the optical spectrum analyzer and not modulus of a real number.

Figure 4.16 Graph plots the absolute value of the ELPG transmission dip with respect to increasing bending curvatures.

The curvature limit of 2 m^{-1} was determined when the resonance wavelength fluctuated away from the original resonance wavelength. From the experimental results, the ELPG yields a sensitivity of 5.07 dBm/m^{-1} with the achievable curvature resolution of $\pm 0.01 \text{ m}^{-1}$. The curvature resolution calculated is dependent on the resolution or sensitivity of the micrometer (0.01 mm). The curvature accuracy is dependent on the accuracy of the measuring instrument, which in this case is the OSA. With the OSA accuracy of $\pm 0.05 \text{ dB}$ and the ELPG sensitivity of 5.07 dBm/m^{-1} , the ELPG curvature accuracy is calculated to be $\pm 0.01 \text{ m}^{-1}$. Hence ELPG can be used to measure small curvature changes, which might be useful for civil structure monitoring. Higher bending range can be achieved with fewer layers of the carbon-fiber composite laminates. Further experiment was carried out on an LPG embedded in a 2-1 configuration, meaning the LPG is embedded between the 1st and 2nd layer of the 3

layers carbon-fiber composite laminates. Results showed that a higher bending curvature range between 0 m^{-1} and 4.98 m^{-1} was achieved. The disadvantage of fewer carbon-fiber composite laminate layers is the reduction in protection for the LPG, which is very close to the surface. Hence there is a trade off balance between measuring range and protection.

There are a few methods to enhance the sensitivity of the ELPG. One method is by etching the cladding but this will reduce the structural strength of the optical fiber, making it more susceptible to damage when used under harsh environmental conditions. The other method is by making use of the higher order cladding modes. Experiments have shown that LPG having the higher order cladding mode and its resonance wavelength at the turning point of the characteristic curve has greatest sensitivity [58]. With the higher-order cladding mode, the modal field of that cladding mode is less confined towards the core and spreads more to the cladding/carbon-fiber interface. Therefore a small amount of bending of the optical fiber will have a significant amount of change to the modal field of the cladding mode and thus the overlap integral of the coupling coefficient. Higher-order cladding modes can be obtained by fabricating an LPG with smaller grating periods.

4.3.2.2 REPEATABILITY, HYSTERESIS AND STABILITY INVESTIGATION

Repeatability and hysteresis in any sensor system is an important area of concern. Repeatability defines the accuracy (trueness and precision) of the measurement methods and results. Hysteresis is the maximum difference in output for any given input (within the specified range) when the value is approached first with increasing, and then with decreasing, input signals. Together they form an important

part of the overall sensor performance. In this investigation, the ELPG was subjected to a sequence of 5 cycles of bending, with curvatures in each cycle ranging from 0m^{-1} to 2m^{-1} . Figure 4.17 shows the results from the repeatability test.

Figure 4.17 Diagram shows a plot of results obtained from the repeatability test.

From the observation in figure 4.17, repeatability tests show that the ELPG exhibits good repeatability. From the results obtained, it was calculated that the ELPG exhibits a repeatability of 98.1 %. The repeatability error calculated was 0.225 dB or 0.07 m^{-1} in amplitude and curvature respectively. This error could be due to system and environmental contributions. System contribution comes from OSA and TLS reading fluctuation. From the manufacturer’s data, the level accuracy for the OSA is $\pm 0.3\text{ dB}$, while the optical output accuracy and optical output reproducibility for the TLS is $\pm 1\text{ dB}$ and $\pm 0.04\text{ dB}$ respectively. Therefore the combined fluctuations from

both OSA and TLS readings have a slight effect on the ELPG's repeatability. Environmental contribution can come from ambient temperature fluctuation. Temperature fluctuations affect not only the resonance wavelength but the transmission dip as well [60]. The effect of temperature on the transmission dip of the ELPG spectrum will be discussed in a later section.

Figure 4.18 Diagram shows the plot of the results obtained during the hysteresis test.

Figure 4.18 shows the results obtain from a single cycle hysteresis test. From the results, it has been demonstrated that the ELPG exhibits low hysteresis property. This is important as it ensures that the ELPG will output consistent readings whenever bending on the ELPG increases and decreases. The hysteresis error was found to be 0.0514 dB or 0.017 m^{-1} in curvature.

The final system performance test looked into the stability characteristic of the sensor as a function of time. To investigate the stability of the ELPG bending sensor

under a fixed bending curvature for a period of time, test was carried out by monitoring the resonance amplitude for a period of 130 minutes, and at a randomly chosen constant curvature of 1.1 m^{-1} . During the 130 minutes period, it was experimentally showed that ELPG exhibits a stability error of $\pm 0.01\text{ dB}$ in amplitude or $\pm 0.003\text{ m}^{-1}$ in curvature, which is equivalent to a percentage error of 0.266% using curvature of 1.1 m^{-1} as a reference. The stability error could partially be due to fluctuation of the power of the light source ($\pm 0.05\text{ dB}$).

4.4 BENDING DIRECTION MEASUREMENT

Results discussed above have been restricted to bending on one side of the ELPG. Same bending procedures were conducted on the opposite side of the ELPG and an interesting phenomenon was observed. The data were recorded and the results are plotted as shown in figure 4.19.

Figure 4.19 Diagram shows the test results of bending on the opposite side of the ELPG.

Observation from the graph showed that as bending curvature was increasing from 0 m^{-1} to 0.626 m^{-1} , the coupling strength of the ELPG increases, and this means that the depth of the resonance dip increases. Beyond the curvature of 0.626 m^{-1} , the coupling strength decreases, and hence the depth of the ELPG's resonance dip decreases, which followed the same response to bending that was recorded from the first experiment. Equation 4.3 shows that coupling strength of the LPG is dependent not only on the coupling coefficient κ , but also on the length of the grating L . It is suggested that when bending was applied perpendicular on the topside which has 4-layers (figure 4.20), the LPG will undergo slight tension due to its off-neutral axis location in the laminate.

Figure 4.20 Diagram shows that compression occurs at the topside of the laminate while the latter experienced tension at the bottom side.

The slight tension resulted in an increase in grating length of the LPG that affects the coupling strength (equation 4.3), by increasing the latter. However, when the coupling strength goes beyond $\pi/2$, the resonance dip decreases. For the LPG used in this experiment, κL was calculated to be 1.456, which was less than 1.571 or $\pi/2$. When the bending curvature on the ELPG increases from 0 m^{-1} to $\sim 0.626 \text{ m}^{-1}$, the

coupling strength increases from 1.456 to 1.571 and this causes an increase of depth of the resonance dip. Beyond 0.626 m^{-1} , the resonance dip decreased as the coupling strength continued to increase beyond $\pi/2$. The initial results are promising as the ELPG can be used not only to give an idea of the magnitude of bending, but is able to tell its bending direction as well. Despite its advantages and capability, current configuration may be insufficient for measuring large bending direction, and hence in order to achieve wider dynamic range for bending measurement in both directions, LPG could be fabricated with coupling strength of $\kappa L \approx \pi/4$ so as to enable the ELPG to have equal measurement range for both bending directions.

What will happen if the LPG is embedded at the neutral axis of the carbon-fiber composite laminate? The neutral axis here means the axis along the fiber where it is located at the center of the whole carbon-fiber composite laminate. To find out, another test was conducted with a LPG embedded at the neutral axis of the 3 x 3 layer or 6 layers laminate. Results are shown in figure 4.21.

Figure 4.21 Experimental results from bending ELPG embedded at neutral axis of a 6 layers laminate. (a) shows the results by bending on one side of the ELPG while (b) shows the results by bending on the opposite side of the ELPG.

It was predicted that the results from bending in both directions will follow the same trend as shown in figure 4.21a. It was however shown that bending in both directions yielded different results (figure 4.21a and 4.21b) that are similar to the one obtained using bending the 4-3 configuration ELPG. One possible reason for this is that the LPG, although was embedded at the neutral axis, was not located exactly at the neutral axis. This could be a result of error during the embedding process as it was done manually. Excessive force applied to flatten the laminate, during the stacking process, could have caused the LPG to move out of the neutral axis. It has to be careful during the embedding process to control the amount of force that will be applied to flatten the laminate. Another ELPG having the LPG embedded in the neutral axis of the 3 x 3 layer carbon-fiber composite material was made and the test was repeated. The experiment results show that bending both sides of the ELPG caused the resonance dip to decrease. This demonstrates that by placing the LPG off the neutral axis in the carbon fiber composite material enables the ELPG to sense both bending and direction of bend.

4.5 SIMULTANEOUS MEASUREMENT OF BENDING AND TEMPERATURE

It has been a fact that temperature fluctuations affect the LPG resonance wavelength. Ng and co-worker had shown the effect of thermal changes has on the LPG resonance dip [60]. Although the changes of the resonance dip due to temperature change can be small as compared to the effect due to bending, the accuracy of the sensor can be compromised when measuring small bending curvatures. There had been numerous ways of temperature compensation techniques being reported over the years [22, 99, 100, 101]. One such method is the use of a matrix inversion (MI) technique to measure bending and temperature simultaneously

proposed by C. C. Ye et al. [102]. This method requires a pair of LPGs which is fabricated on different fiber type so that they response differently to the same bending and temperature changes. For each LPG, there is a mathematic expression which expresses that LPG's sensitivity to bending and temperature. Hence with two LPGs, there exist two equations which can be solved using simultaneous equation approach or Matrix Inversion method. The MI method has also been demonstrated for simultaneous measurements of both strain and temperature with the aid of two superimposed FBG [103]. Measurement of both quantities simultaneously has an added advantage as it allows one to obtain both bending and temperature without using additional equipment. In this project, the 2×2 MI method will be applied for the case of ELPG bending sensor for simultaneous measurement of bending curvature and temperature.

4.5.1

BACKGROUND THEORY

An LPG is made up of uniformly photo-induced refractive index modulation along the core of single mode optical fiber with a modulation period in the range of hundreds of microns. Upon satisfying the phase-matching condition, the LPG couples the fundamental guided core mode into numerous discrete guided cladding modes. The phase-matching equation for the coupling is expressed as follows:

$$\lambda_{res} = (n_{core}^{eff} - n_{cladd,m}^{eff}) \Lambda \quad (4.6)$$

where λ_{res} is the resonance wavelength. Λ is the grating period. n_{core}^{eff} is the effective refractive index of the fundamental core mode and $n_{cladd,m}^{eff}$ is the effective refractive index of the m^{th} cladding mode.

From the spectral response of the ELPG bending sensor, its resonance dip or coupling strength changes with different bending curvatures, while the resonance wavelength remains relatively constant. The coupling strength that governs the transfer of energy between core and cladding modes can be expressed as equation 4.3:

$$C = \sin^2(\kappa L) \quad (4.7)$$

where L and κ are the grating length and coupling coefficient respectively. In a controlled environment, such as a laboratory, the resonance dip or coupling strength change from the bending sensor is mainly due to bending and isolated from external perturbation, such as temperature, relative humidity changes, etc. In an actual implementation of the bending sensor, the ELPG may also be subjected to such environmental perturbations.

A change in coupling strength of the embedded LPG bending sensor as a function of both bending and temperature can be written as:

$$\Delta Amp = K_B \Delta Curvature + K_T \Delta Temp \quad (4.8)$$

where ΔAmp is the change in resonance amplitude of the embedded LPG bending sensor spectrum, while K_B and K_T are the bending and temperature coefficients of the sensor respectively. With two unknowns in an equation, a pair of equations will be required to solve for both the bending curvature and the temperature simultaneously. These two simultaneous equations can be expressed in a matrix form as follows,

$$\begin{pmatrix} \Delta Amp_1 \\ \Delta Amp_2 \end{pmatrix} = \begin{bmatrix} K_{B1} & K_{T1} \\ K_{B2} & K_{T2} \end{bmatrix} \begin{pmatrix} \Delta Curvature \\ \Delta Temp \end{pmatrix} \quad (4.9)$$

The unknown change, $\Delta Curvature$ and $\Delta Temp$, can then be solved by first order simultaneous equations giving,

$$\begin{pmatrix} \Delta Curvature \\ \Delta Temp \end{pmatrix} = \begin{bmatrix} K_{B1} & K_{T1} \\ K_{B2} & K_{T2} \end{bmatrix}^{-1} \begin{pmatrix} \Delta Amp_1 \\ \Delta Amp_2 \end{pmatrix} \quad (4.10)$$

Hence given the bending (K_{B1} and K_{B2}) and temperature (K_{T1} and K_{T2}) coefficients for both ELPG and given the direct intensity readings (ΔAmp_1 and ΔAmp_2) from the ELPG, changes in bending curvature and temperature experienced by the ELPG can be computed using equation 4.10. Experimental results using MI method for measuring both bending curvature and temperature simultaneously will be presented in the next section.

4.5.2

RESULTS AND DISCUSSIONS

For this experiment, two LPGs were fabricated using the amplitude mask technique fabricated from the same amplitude mask with periodicity of 450 μm . Of the two LPGs, one of them was fabricated using a H_2 -loaded standard SMF-28 optical fiber and the other LPG was fabricated on a B/Ge co-doped photosensitive optical fiber, Metrotek PS1500. For the H_2 -loaded LPG, it had to go through annealing at a temperature of 85 $^{\circ}\text{C}$ for at least 5hrs in order to stabilize the LPG spectrum. On the other hand, B-Ge co-doped LPG needs not go through the same annealing process. The spectral response of the H_2 -loaded ELPG to temperature variation is shown in figure 4.23.

Figure 4.23 Figure shows that effect of temperature change on the wavelength and coupling strength of the SMF ELPG bending sensor.

Figure 4.23 shows the change of the absolute transmission dip and resonance wavelength of the ELPG spectrum with temperature for temperature range between 25°C and 80°C. When temperature increases, not only were there a red shift in the resonance wavelength, the coupling strength increases as well, as can be seen in the figure. The increase of the coupling strength is dependent on the initial value κL , after the fabrication process, as it follows a periodic function of $\sin^2(\kappa L)$. The dependency of the grating strength to temperature depends on both the temperature sensitivity of the resonance wavelength and the temperature sensitivity of the overlap integral [60].

To determine the bending and temperature coefficients of the two LPG bending sensors (H_2 loaded and B/Ge doped), individual calibration tests were carried out on the H_2 -loaded LPG bending sensor and the B/Ge co-doped bending sensor. From the tests, the bending coefficients for both the H_2 -loaded ELPG ($K_{B(H_2)}$) and the B/Ge

co-doped ELPG ($K_{B(Bo/Ge)}$) are found to be 5.0745 dB/m⁻¹ and 0.5721 dB/m⁻¹ respectively. The temperature coefficient for the H₂-loaded ELPG ($K_{T(H_2)}$) and the B-Ge co-doped ELPG ($K_{T(Bo/Ge)}$) are 0.0071 dB/°C and -0.01802 dB/°C respectively. Using equation 4.8, the change in resonance amplitude of both sensors can hence be written as

$$\begin{pmatrix} \Delta Amp_1 \\ \Delta Amp_2 \end{pmatrix} = \begin{bmatrix} 5.0745 & 0.0071 \\ 0.5721 & -0.01802 \end{bmatrix} \begin{pmatrix} \Delta Curvature \\ \Delta Temp \end{pmatrix} \tag{4.10}$$

Hence the change in both curvature and temperature can be obtained by matrix inversion, equation 4.9 and yields;

$$\begin{pmatrix} \Delta Curvature \\ \Delta Temp \end{pmatrix} = \begin{bmatrix} 0.1887 & 0.0743 \\ 5.9903 & -53.1337 \end{bmatrix} \begin{pmatrix} \Delta Amp_1 \\ \Delta Amp_2 \end{pmatrix} \tag{4.11}$$

Curvature (m ⁻¹)	Temperature (°C)	Experimentally measured (dB)	Calculated (dB)	Error (dB)	Error (%)
0.75	19	-15.53	-14.98	0.5436	5.96 %
1.00	19	-14.12	-13.72	0.4036	4.43 %
1.25	19	-12.75	-12.45	0.3027	3.32 %
1.50	19	-11.46	-11.18	0.2807	3.08 %
1.75	19	-10.24	-9.91	0.3272	3.59 %

Table 4.1 Measured and calculated resonance dip power of the H₂-loaded ELPG bending sensor, when the temperature is maintained constant.

Table 4.1 tabulates the comparison of the differences between the experimentally measured and the MI calculated ELPG’s resonance dip depth for the H₂-loaded ELPG for a known curvature, while the temperature was maintained constant at 19 °C ±1 °C. From the results, the average percentage error was calculated to be approximately 4 %.

Chapter 4

Application of Embedded Long Period Gratings
(ELPG) as Bending Sensor

Curvature (m ⁻¹)	Temperature (°C)	Experimentally measured (dB)	Calculated (dB)	Error (dB)	Error (%)
1.25	25	-12.33	-12.40	-0.0747	0.82 %
1.25	35	-12.27	-12.33	-0.0637	0.70 %
1.25	45	-12.19	-12.26	-0.0727	0.80 %
1.25	55	-12.12	-12.19	-0.0717	0.79 %
1.25	65	-12.05	-12.12	-0.0707	0.78 %

Table 4.2 Measured and calculated resonance dip power of the H₂-loaded ELPG

bending sensor, when the bend curvature is maintained constant.

Table 4.2 tabulates the comparison of the differences between the actual measured and the MI calculated ELPG’s resonance dip depth for the H₂-loaded ELPG bending sensor for a known temperature, while maintaining a constant bending curvature. The temperature was ramped from 25 °C to 65 °C in steps of 10 °C while the curvature was kept approximately at 1.252 m⁻¹. The percentage error is approximately 0.8 %. By comparing the percentage error obtained for table 4.2 and table 4.1, it can be observed that both tables do not have similar percentage errors. The percentage error is higher for table 4.1, which could due to the inconsistency in the bending curvatures as the tuning of the micrometer is done manually. Same tests were also carried out using B/Ge co-doped ELPG bending sensor to find out if this type of optical fiber has the same effect on the percentage error differences as that of the H₂-loaded ELPG. Comparison between experimentally measured and calculated results from the B/Ge co-doped ELPG also yields similar trend as observed in table 4.1 and table 4.2.

Additional tests were conducted using both H₂-loaded and B-Ge ELPG bending sensors, which involve subjecting these ELPGs to a random set of bending curvatures and temperatures. The readings from the ELPGs were recorded for

comparison with the calculated curvature values, as shown in Table 4.3.

H ₂ -loaded ELPG				
Temperature (°C)	Measured Curvature (m ⁻¹)	Calculated Curvature (m ⁻¹)	Difference from measured curvature (m ⁻¹)	Percentage error (%)
37	1.8212	1.6848	0.1364	4.97
43	1.6016	1.4526	0.1490	5.43
44	1.8212	1.6698	0.1514	5.51
B-Ge Co-doped ELPG				
Temperature (°C)	Measured Curvature (m ⁻¹)	Calculated Curvature (m ⁻¹)	Difference from measured curvature (m ⁻¹)	Percentage error (%)
37	1.8212	1.6848	0.1352	4.92
43	1.6016	1.4526	0.1474	5.37
44	1.8212	1.6698	0.1502	5.47

Table 4.3 A comparison of calculated curvature against experimentally measured curvature. Results from both fiber types show similar percentage error.

In the simultaneous measurements of both bending curvature and temperature for civil structures monitoring, bending measurement will be of higher importance as compared to temperature measurement. Table 4.3 shows the values of calculated curvatures and experimentally measured curvatures. The results show that the percentage errors between the measured and calculated curvatures and temperature are less than 6 %. Better accuracy or lower error, in the final result, can be further achieved through the data processing methods such as neural networks [104].

From these experimental investigations, the ELPG offers great potential for immediate structural applications. As it is embedded in the carbon-fiber composite laminate, the LPG is well protected and thus can be applied in applications working in harsh environment conditions. For example it can be surface mounted onto any civil structures such as bridges, skyscraper and offshore oilrigs. In aerospace applications,

the ELPG can be implemented for stress monitoring on the airframe or wings of commercial airliners or military aircrafts.

Results from the characterisation of the ELPG bending sensor shows that the sensor exhibits a sensitivity of 5.07 dBm/m^{-1} and with the curvature resolution of $\pm 0.01 \text{ m}^{-1}$. Cyclic tests performed on the ELPG showed that the ELPG exhibits 98.1% repeatability and hysteresis error of 0.0514 dB or 0.017 m^{-1} . In addition to the characterisation of the ELPG, further test shows the direction detection capability of the ELPG bending sensor. With a single ELPG bending sensor, the sensor can detect both bending direction and curvature.

Since the output of the ELPG is intensity based, it can be demodulated using existing photodetector and electronics system, thus reducing the operating and maintenance cost. Despite the ease of demodulation and low operating cost, the downside of intensity-based system is that any DC fluctuations in the light source output will cause fluctuations in the ELPG's output readings, thus may influence the accuracy of the results. To overcome this drawback, a balanced photodetector can be used to cancel out the DC fluctuations from the light source, leaving only the actual data. Before pumping the light source into the ELPG, the light source will be split into a reference arm and a sensing arm via a coupler. The balance detector is then used to compare the reference and the sensing arms and then cancel out any DC fluctuation from the light source, if any arises.

CHAPTER 5: ELPG for Dynamic Gain Equalization in Erbium-Doped Fiber Amplifier

5.1

INTRODUCTION

Although the main purpose of ELPG is for bend sensing, its spectral response characteristics to bending provide a potential application in fiber optic communications. In this section, a novel technique using the ELPG to dynamically equalize the erbium-doped fiber amplifier's optical gain spectrum will be presented.

Erbium-doped fiber amplifiers (EDFAs) have been broadly used as optical amplifiers in long haul dense wavelength-division multiplexing (DWDM) optical communication networks due to the coincidence of the EDFA's amplification window with the transmission window of silica-based optical fiber, 1525 nm to 1565 nm. Using electrical-based amplifier, individual optical signal is first converted to electrical signal, amplified electrically and then converted back to optical signals for forward transmission into the next section of the optical fiber network. An EDF allows all the optical signals in the network to be amplified directly without the need for the electrical conversion process. Other advantages of using EDFA are:

- It is an all fiber based system and hence there is lower insertion loss as compared to electrical based amplifier.
- It is immune to electromagnetic interference
- It has higher optical bandwidth

For uniform amplification of the optical signals across the optical communication windows in a DWDM network using the EDFA, the EDFA optical gain spectrum must be relatively constant across the optical communication spectral range. This is however not the case as the EDFA's optical gain spectrum has a peak at

around 1530 nm wavelength, as shown in figure 5.1. This is undesirable as it is unable to provide proper amplification to every channel in the DWDM communication network.

Figure 5.1 Optical gain spectrum of erbium-doped fiber amplifier with different pump power.

Hence in order to achieve uniform optical gain spectrum, an attenuator will be required to reduce the gain in the vicinity of the 1530 nm wavelength region. Several methods have been proposed for this gain equalization, such as using micro-opto-mechanical interferometric mirror with variable reflectivity [105], using an acousto-optic tunable filter [106] and using a cascade of variable couplers and delay lines [107], etc. However these methods are complicated and have high insertion losses. Due to its simplicity and low insertion loss, an LPG has been used for gain equalization of the EDFA gain spectrum. The peak at the 1530 nm region of the EDFA optical gain spectrum varies with different pump power. From figure 5.1, it can be shown experimentally that as pump power increases, the peak at 1530 nm increases. Hence dynamic gain equalization, whereby the level of attenuation can be adjusted for

different pump powers, is required in order to maintain a relatively uniform gain profile across the whole of the optical gain spectrum regardless of its pump power.

Techniques that have been demonstrated with LPG as a variable attenuator include the Mach-Zehnder interferometer technique [108], the thermal variation technique [107] and the bending of CO₂ fabricated LPG technique [35]. In reference [35] the LPG resonance dip varies with different bending curvature, while its resonance wavelength remains relatively constant. CO₂ fabrication method has the advantage of producing gratings without the need for photosensitive fiber. It has been pointed out that the bending of CO₂ fabricated LPG with standard single mode fiber (SMF), like the case of excimer fabricated LPG, will result in both changes in its resonance wavelength and resonance dip [35]. Hence bending-insensitive fiber was used to ensure that the LPG resonance wavelength is insensitive to bending but it adds to the overall cost to the system. Although the technique used in reference [35] allows only change in resonance dip and not resonance wavelength with bending, this characteristic is critically dependent on the direction of bending with respect to the direction of the CO₂ laser applied on the optical fiber. In any other directions, both LPG's resonance dip and resonance wavelength will change with different bending curvatures.

Same dynamic response however has been achieved using ELPG, which has been demonstrated for dynamic gain equalization of EDFA. The advantage of using the ELPG is that there is no requirement for the use of bending-insensitive fiber in order to achieve the constant resonance wavelength while bending. Thus it will be more economical as SMF is very much cheaper as compared to bending-insensitive

fiber. In addition, as ELPG is fabricated using normal UV laser, the refractive index change induced across the transversal side of the core is uniform. Hence the bending of ELPG is not orientation dependent. Last but not least, by embedding the LPG in between the carbon fiber composite material, the LPG as a whole is more rugged.

5.2

EXPERIMENTAL SETUP

Same experimental setup as that used for testing the bending sensor was used to induce bending on the ELPG to dynamically tune the attenuation of the EDFA, except that the LPG was fabricated with its resonance wavelength matching that of the peak wavelength in the EDFA gain spectrum, which is 1530 nm. The grating period of the LPG used was 475 μm .

Three sets of experiments were carried out in this test. Firstly the optical gain spectrum of the EDFA at different pump power was recorded, as shown in figure 5.1. This set of data was used as a reference in which the second set of experiment will be based on. The second set of experiment involved the investigation of the transmission characteristics of the ELPG with bending. The purpose of this test is to obtain the relationship between the bending curvature and the depth of the resonance dip in the ELPG's transmission spectrum. By studying the resonance dip change of the ELPG during bending, the actual bending curvature can be known. This in turn can be used to control the ELPG transmission spectrum such that the depth of the resonance dip matches that of the peak of the EDFA optical gain spectrum obtained from the first experiment.

Figure 5.2 Experimental setup of EDFA with ELPG for dynamic gain equalization.

In the last set of experiment, the ELPG was integrated with the tunable gain EDFA, as shown in figure 5.2. With one end of the ELPG connected to the EDFA, the optical output from the ELPG was monitored via an optical spectrum analyzer or OSA. The OSA used in the experiment is Ando AQ6317. In the next section, the results from the tests will be presented and discussed.

5.3

RESULTS AND DISCUSSIONS

From the experimental results, as shown in figure 5.3, the depth of the ELPG resonance dip changes while its resonance wavelength remains constant at 1530nm. These results thus reassure the possibility of using ELPG as an optical device for dynamic EDFA gain equalization as the risk of wavelength shift due to bending is low without complicated optical setups.

Figure 5.3 Experimental results show that the ELPG resonance dip reduces with increased bending while its resonance wavelength remains at 1530nm.

A relationship between bending curvature and resonance dip has to be achieved so that one would be able to know the amount of bending to be given to match that of the peak amplitude of the EDFA gain spectrum. Figure 5.4 depicts a characteristic curve which plots the absolute value of the ELPG resonance dip against its bending curvatures. From the EDFA gain spectrum and at maximum pump power, the difference between the spectral peak at 1530nm and other wavelengths is approximately 10 dB (figure 5.1), while the total difference of the ELPG resonance dip, over the range of bending curvatures, is 16 dB. Based on the ELPG characteristic curve, the ELPG has to be bent to a curvature of approximately 0.8 m^{-1} in order to flatten the EDFA's peak at 1530 nm.

Figure 5.4 ELPG characteristic curve which shows the absolute values of the resonance dip against bending curvatures.

Once the adjustment of the bending curvature on the ELPG had been made in order to produce the dip difference of 10 dB in the ELPG's resonance dip, the ELPG transmission spectrum is then coupled into the EDFA gain spectrum. The output spectrum of the EDFA is recorded and plotted as shown in figure 5.5. The EDFA transmission spectrum, in figure 5.5, depicts the optical gain spectrum without and with gain equalization using ELPG. Gain equalization was achieved using ELPG, which yields a uniform gain across the whole spectral range of the EDFA gain spectrum. A 1 dB peak to peak ripple was noticed on the higher wavelength side, away from 1530 nm region, of the gain spectrum. This could be due to the ripples formed adjacent to ELPG resonance dip of the transmission spectrum as the dip decreases, shown in fig. 5.3. The 1 dB peak to peak ripple is similar to the non-dynamic commercial LPG gain flattener, which is around ± 0.5 dB.

Figure 5.5 EDFA transmission spectrum without gain equalization (upper curve) and with gain equalization using ELPG (bottom curve).

Having demonstrated the ELPG for static compensation of the EDFA gain spectrum, we next demonstrate the use of ELPG for dynamic compensation of the EDFA gain spectrum at different pump currents. Experiments were carried out at three different pump currents, namely at 80 mA, 100 mA and 200 mA.

Figure 5.6 Dynamic ELPG compensated EDFA gain spectrum at pump currents of 80mA, 100mA and 200mA.

Figure 5.6 shows the combined EDFA gain spectral at different pump currents, which were dynamically compensated by bending the ELPG. From the experimental results, it can be seen that, the ELPG can be used for dynamic gain equalization of the EDFA just by changing the bending curvature of the ELPG. For a lower pump current of 80 mA, a larger bending curvature will be needed as compared to the higher pump current, as the peak amplitude for the EDFA gain spectrum at 80mA is smaller than that at 200 mA. Hence to match the smaller peak amplitude, the ELPG has to be subjected to a bigger bending curvature so that the resonance dip can be reduced to the desired value.

Since the ELPG is protected by carbon-fiber composite, it is rugged enough to be used under any condition. The whole process of dynamic gain equalization can be automated and integrated with existing optical communications systems. A flow chart that illustrates the automation control is shown in figure 5.7.

Figure 5.7 Block diagram of an automated ELPG gain equalization system.

During the automated dynamic gain equalization process, a computer with onboard DAQ card can be used to monitor the EDFA pump current. The current can

then be compared with its database. This database contains the values of all the EDFA pump currents which give different peak amplitude difference in the EDFA gain spectrum at 1530 nm.

When the pump current, being monitored, matches that of the value stored in the database, the computer then sends a signal, via the DAQ card, to the motor controller. Upon receiving the appropriate signal from the computer, the motor controller will then induce the appropriate bending to the ELPG so as to achieve a uniform EDFA gain spectrum at the output of the ELPG. A feedback will be fed back to the computer system by monitoring the peak difference at the 1530nm of the EDFA gain spectrum. This is to ensure that no further changes in bending curvature on the ELPG is required once the uniform gain is achieved at the EDFA gain spectrum.

In this chapter, the ELPG has been exploited to demonstrate a novel technique for gain equalization of the EDFA's optical gain spectrum. This is made possible because the resonance wavelength of the ELPG remains unchanged while its resonance dip changes with different bending curvatures applied on the ELPG. If the ELPG is fabricated such that its resonance wavelength coincide with the EDFA's optical peak, at 1530nm, in the gain spectrum, the amplitude of the EDFA's peak can be modified by changing the ELPG resonance dip through bending. It has also been demonstrated in this chapter that ELPG can be used to dynamically compensate the EDFA's optical gain spectrum at different level pump current in the EDFA.

**CHAPTER 6: High Relative Humidity Measurements Using
Gelatin-Coated Long-Period Gratings Sensor****6.1****INTRODUCTION**

As mentioned in the introduction, that relative humidity (RH) sensing is important for many applications and a review of various types of optical fiber based RH sensors shows that none is able to measure high RH. High RH sensing plays a very important role in determining the stress state and moisture content in soil, which determines the shear strength, volume change and hydraulic behaviour of the soil [14]. High RH sensing is made possible with the novel intensity based gelatine-coated LPG RH sensor. This chapter will present the development and characterization work on this novel sensor.

Optical fiber humidity sensing operates based on the interaction between the evanescence field of the light propagating in the fiber and the humidity sensitive coating surrounding the area of interaction at the fiber/coating interface. The coating changes its optical characteristics, such as refractive index, at different level of RH such that the interaction with the evanescence field will result in the change in the properties of the light which will be detected at the other end of the optical fiber.

The presentation will begin with the discussions on the coatings used for the LPG RH sensor, followed by the experimental setup and then finally, results and discussions.

6.2**COATINGS**

Two types of coatings were considered in this part of the work, namely gelatin and polyvinyl alcohol (PVA), primarily due to their availability. Both PVA and gelatin

have been used as sensing material itself [111, 32] and as surface coating material in the RH sensing devices [28, 30]. The reason for using PVA and gelatin is due to their hydrophilic nature of these polymers. Another advantage of using PVA and gelatin is that they both exhibit good coating properties, adhesion, uniformity and thickness.

As a sensing element, PVA has been used as in RH sensing research. Its RH measurement ranges between 55 %RH and 85 %RH [110]. Beyond that, the sensitivity flattened out. Another property of PVA, if use as a binding material, is that PVA will turn opalescent when exposed to high RH, hence light will be scattered. On the other hand, when exposed to high RH, gelatin remains optically clear, allowing light to be transmitted and thus achieving maximum interaction between light and the gelatin coating [111].

Gelatin is a protein extracted from animal hides, bone, and sinew that belongs to the class of substances known as hydrocolloid ("water loving") polymers, which also includes other proteins, gums, starches, and a wide variety of synthetic polymers. Gelatin, primarily collagen, is a long fibrous protein that makes up the mechanically strong but elastic tissue of the body. The structure of the protein consists of a triple helix of repeating amino acid sequence and a single globular head portion that makes up a small part of the protein itself. The long repeating sequence is not soluble in water and tends to self-associate. However, once it is boiled, it dissociates into separate strands at the molecular level. When the gelatin, in powder form, is dissolved in hot water, it returns to its molecular strands that move about randomly in the solution. Upon cooling, if the concentration of the chains is high enough, they may entangle with each other. This entanglement provides the molecular strength (elasticity) of the

hydrogel. Hydrogels can be considered as a three-dimensional web of polymer chains with a highly irregular structure, which has the capability to fluctuate. The open and fluctuating structure leaves room for things to diffuse through the hydrogel within the water matrix. However once the water matrix is removed via evaporation after cooling, the whole structure would be a collapsed 3D web. Gelatin, like most proteins, has a higher effective atomic number than H₂O. As a result, the density of gelatin is higher than water and hence the refractive index of gelatin is higher than that of water. Solid gelatin has a refractive index of 1.53. The change of gelatin refractive index is dependent on the water content. The change in optical properties with RH can be seen following the relation for the refractive index n of a composite material [32] (eg. Gelatin and water);

$$\frac{n^2 - 1}{n^2 + 2} = \sum_i \left[\frac{\rho_i R_i}{M_i} \right] \quad (6.1)$$

where ρ_i is density, M_i is the molecular weight and R_i is the molecular refractivity of the i -th component material. Thus a change in any of the three parameters on the right-hand-side of equation 6.1 will affect the refractive index of the polymer. As the RH increases, more water vapor diffuses into the gelatin and reduces its refractive index. In addition the gelatin swells with increase in water content.

Figure 6.1 System setup for fabrication LPG.

The LPG used for the experiment was fabricated using the amplitude mask technique as shown in figure 6.1. Since the optical fiber used is the standard telecommunication fiber, Corning SMF-28, it had to be hydrogen-loaded for 7 days at 1500 psi and at a temperature of 70 °C in order to photosensitize the fiber. A broadband source was launched into one end of the photosensitive fiber while the other end was connected to an optical spectrum analyzer (OSA), ANDO AQ6317. A section of 10 mm long on the optical fiber was scanned repeatedly through a 300 μm amplitude mask using a frequency doubled Argon-Ion UV laser lasing at the wavelength of 244 nm, and at a power of 70 mW. In this experiment, the LPG was fabricated with the cladding mode having the highest wavelength attenuation band within the optical communication window of 1520 nm to 1620 nm. To stabilize the LPG spectrum, all the optical fibers were annealed at 85 °C for 18 hrs.

The LPG was coated with liquid gelatin after annealing. The gelatin solution was prepared by mixing dry gelatin powder with distilled water. The ratio was 1 g of gelatin with 20 g of distilled water, or 5 % by weight of the solution. The solution was then heated up to 65 °C for the gelatin to be completely dissolved. The gelatin was

then coated on the LPG and the coated LPG was then left to dry for 24 hrs. Figure 6.2 shows the prototype of the LPG high relative humidity sensor.

Figure 6.2 LPG high humidity sensor prototype packaged together with a brass tube to prevent bending (Dimensions in cm).

The gelatin coated LPG was placed in a brass tube. An opening on the top side of the brass tube was created to facilitate the interaction between water vapor and the gelatin, refer to figure 6.2. Both ends of the tube were set using two-part epoxy, with the LPG held straight, so as to minimize any bending loss on the LPG.

To conduct the humidity tests, the LPG RH sensor was placed in a climate control chamber (Feutron KPK35) where both humidity and temperature can be controlled, shown in figure 6.3. The climate control chamber has a temperature and relative humidity accuracy of ± 0.1 °C and 0.1 %RH respectively. Due to the limitation on the lowest possible RH that could be achieved by the chamber, the test started from approximately 43 %RH. The humidity was increased stepwise to 99 %RH, at 5 %RH step intervals from 43 %RH to 90 %RH and 1 %RH step intervals from 90 % to 99 %. The optical spectrum analyzer, which was synchronized with a tunable laser source

(TLS) (ANDO AQ4321D), was used for the spectral measurements. The chamber temperature was maintained at 25 °C throughout the experiments. The OSA has a level resolution of 0.01 dB and the TLS has a level stability of 0.05 dB.

Figure 6.3 Experimental setup shows that the gelatin-coated LPG was placed in the climate control chamber during test.

6.4

RESULTS AND DISCUSSIONS

From the experimental results, it was found that the gelatin-coated LPG spectrum responded very well to high RH. This is the first time this phenomenon was observed and investigation was conducted for possible explanations. To investigate the gelatin-coated LPG RH sensor's performance, characterization of the sensor's sensitivity, repeatability, hysteresis and stability were conducted. From the investigations, results have suggested that the gelatin-coated LPG high RH sensor demonstrated its ability for high RH sensing. Apart from the characterization of sensor, issues on sensitivity dependency of the gelatin-coated LPG RH sensor on different cladding modes order of the LPG spectrum and gelatin concentrations were also investigated.

Prior to coating the gelatin onto the LPG, the refractive index of aqueous and solid gelatin was measured. The purpose for doing this is to enable a better prediction of the LPG response after coating has been applied onto the LPG. The refractive index of the aqueous gelatin was measured using a refractometer, Kyoto Electronics RA-130, which gave a value of 1.3408. Aqueous Gelatin was later spin-coated on a glass plate and dried under room temperature for 24 hrs. Another reading of the refractive index of dehydrated gelatin coating at a thickness of 6.836 μm (using Metricon 2010 Prism Coupler) yielded a refractive index value of 1.474. This value shows that the refractive index of dehydrated gelatin is higher than that of cladding. The spectral response to external medium refractive index higher than that of cladding has been discussed in section 2.5.3 of chapter 2.

Spectral measurements were also recorded during the process of coating the LPG. Results before and after coating are shown in figure 6.4 and figure 6.5 respectively.

Figure 6.4 The resonance wavelength in the transmission spectrum of a bare LPG is located at 1543.186 nm.

Figure 6.5 Comparing with figure 6.4, the resonance wavelength had shifted 6.486nm towards the shorter wavelength or blue shift after the gelatin was applied and dehydrated.

From the above figures, it can be observed that the resonance wavelength of the LPG with dehydrated gelatin coating exhibits a blue shift as compared to the same bare LPG. As presented in chapter 2, the coupling of the fundamental core mode to the discrete cladding mode, in the LPG, is governed by the phase matching equation, which is defined as, equation 2.23:

$$\lambda_{res} = (n_{core}^{eff} - n_{cladd,m}^{eff}) \Lambda \quad (6.2)$$

where λ_{res} is the resonance wavelength. n_{core}^{eff} and $n_{cladd,m}^{eff}$ are the effective indices of the fundamental core mode and cladding mode of m -th order respectively. Λ is the grating periodicity. $n_{cladd,m}^{eff}$ is dependent on the gelatin's refractive index. Using equation 6.2, the LPG's resonance wavelength will shift to the shorter wavelength or blue shift when the external medium refractive index is greater than that of air but lower than that of cladding. Thus the blue shift in the LPG resonance wavelength as observed in figure 6.5 shows that there is an increase in the cladding mode effective

refractive index, which is contributed by the presence of gelatin coating. This was proven experimentally by subjecting the LPG to oil of different refractive indexes (Lightspan Application Technology), as shown in figure 6.6.

The LPG's spectral response to the presence of external coating changes when the refractive index of the oil is higher than that of cladding whereby the LPG's resonance wavelength will no longer be shifting to the shorter wavelength side. Instead it remains close to that the original position before oil has been applied, as shown in figure 6.6. As the refractive index of the oil is higher than that of cladding, the cladding modes will not be guided under total internal reflection. Instead theses modes will be subjected to Fresnel reflection and Fresnel refraction and the phase matching condition was rendered invalid [69].

Results from figure 6.6 show that the LPG exhibits greatest sensitivity when the oil's refractive index is lower but close to that of the cladding. This high sensitivity is apparent by observing a larger shift in the resonance wavelength as compared to the case when the refractive index of the oil is much lower than that of cladding. In addition, a great change in the depth of the resonance dip was also recorded. From figure 6.7, it can be observed that the grating's coupling strength reduces dramatically, as seen as the reduction of depth of the resonance dip, as the oil's refractive index approaches that of the cladding.

Figure 6.6 Figure shows the wavelength shift of the LPG with respect to refractive index of external medium.

Figure 6.7 Figure shows the coupling strength changes of the LPG with different external refractive index.

Despite the fact that the earlier refractive index measurement test conducted on the dehydrated gelatin was 1.474, which is higher than that of cladding, the blue shift from the gelatin-coated LPG's resonance wavelength suggested is due to an increase in cladding mode effective refractive index. Experimental and theoretical studies on

thin-film overlay coating on LPG showed that the resonance wavelength shift of the LPG is dependent on the thickness of the coatings with refractive indices higher than the cladding [112, 113, 114]. From photos taken using a scanning electron microscope (SEM), it was estimated that the thickness of the gelatin coated onto the LPG used in the experiment was approximately 297.5 nm. Both references [112] and [113] have demonstrated that as the coating thickness increases, the resonance wavelength was displaced towards the shorter wavelength. The reason for the shift is because, as the overlay coating thickness increases, the cladding mode effective refractive index increases until a critical point is reached. At this point, the lowest cladding mode, with the highest effective refractive index, is being guided by the overlay coating, resulting in the loss of that cladding mode. When this happens, there is a re-organization of cladding modes. Higher order cladding modes will shift leftward to recover the previous modes, as shown in figure 6.8 [113].

Figure 6.8. Shift of resonance wavelength caused by coupling between core mode and the LP_{07} and LP_{08} cladding modes as a function of the overlay thickness [113].

Figure 6.8 shows the shift of LP_{08} to recover LP_{07} , which the latter has shifted to recover the previous cladding mode. Shifting of the resonance wavelength is dependent on both the overlay coating thickness and the refractive index of the overlay material [115, 116]. However there exists a region of maximum resonance wavelength

shift, depending overlay coating thickness and refractive index. In figure 6.8, the region where maximum resonance wavelength shift occurs, has an overlay coating thickness of 300 nm. Before and after 300nm, the shift is small. By optimizing the overlay coating thickness such that the cladding mode falls within the region of the maximum wavelength shift, the LPG sensitivity can be greatly enhanced (by a factor of 12.98) as a sensor for sensing surrounding medium's refractive index [116].

6.4.1 PHENOMENON

Figure 6.9 Graph shows the spectrum response of the gelatin-coated LPG when subjected to different values of relative humidity.

It can be observed from figure 6.9 that the gelatin-coated LPG RH sensor spectrum responds to a range of relative humidity, 43 %RH to 99 %RH. Two observations can be made;

1. The graph shows that as the RH increases, the coupling strength of the grating decreases and results in the reduction of the LPG's resonance dip. The most significant spectral response from the LPG to RH occurs when the RH goes beyond 90 %RH. This high sensitivity allows the gelatin-coated LPG to be used as a sensor for sensing high RH. One advantage of using intensity-modulated sensors is that the demodulation of the signal is simple and hence only low cost and stable photodiode circuitry is required.

2. A small shift in the resonance wavelength towards the shorter wavelengths or blue shift was noticed. However, the rate of change of wavelength with RH is lower than the rate of change of resonance dip with RH. The changes in the coupling strength and the blue shift of the spectrum can be attributed to the change in the gelatin coating's refractive index as the RH changes. It is suspected that the average refractive index of the gelatin coating is close to the refractive index of the cladding region. This is due to the big change in the resonance dip of the highest wavelength attenuation band as the average refractive index of the gelatin coating changes with RH.

For an LPG, its coupling strength is governed by the equation given as follows, equation 2.45:

$$C = \sin^2(\kappa^m L) \quad (6.3)$$

where κ^m and L are the coupling coefficient of the m -th cladding mode and the grating length respectively. From equation 6.3, the coupling strength of a LPG is a function of κ^m and L . κ^m is given by,

$$\kappa^m = \frac{\pi |A_N|}{\lambda^m} \eta^m \quad (6.4)$$

where A_N is the Fourier coefficients defined in chapter 2 and η^m is the overlap integral as defined by equation 2.37 and re-stated in equation 6.5,

$$\eta^m = \frac{\left| \int_0^a \Delta n E_{0l}(r) E_{cl}^m(r) r dr \right|}{\sqrt{\int_0^\infty (E_{0l}(r))^2 r dr \int_0^\infty (E_{cl}^m(r))^2 r dr}} \quad (6.5)$$

where a is the core radius, $k = \frac{2\pi}{\lambda^m}$, $E_{0l}(r)$ and $E_{cl}^m(r)$ are the electric field distribution of the fundamental guided mode and the circularly-symmetric cladding mode of order m respectively. η^m is the overlap integral between the fundamental guided mode and the cladding modes in the core region.

As the length L of the gelatin-coated LPG remains unchanged, the reduction of LPG resonance dip when the RH increases is a result of the reduction of overlap integral in the coupling strength. This reduction of the overlap integral is related to the increase in the gelatin coating's refractive index. The reason is that when the gelatin coating's refractive index increases due to increase of RH, the effective refractive index seen by the cladding mode increases. As the cladding mode effective refractive index increases and approaches that of the cladding, more energy from the cladding mode will be lost into the external coating. The remaining cladding mode energy inside the cladding region reduces. As a result there will be a reduction of energy exchanged between the fundamental guided mode and the cladding mode along the grating region in the core of the optical fiber and hence the overlap integral reduces.

6.4.2 SENSOR PERFORMANCE CHARACTERIZATIONS

To understand the gelatin-coated LPG RH sensor’s performance, a series of characterization tests was executed. This involved the study of the sensor’s response curve, sensitivity, repeatability, hysteresis and stability. From the characterization test, the results show that the response curve of the gelatin-coated LPG RH sensor is not sensitive at low relative humidity of between 43 %RH and 90 %RH, but is highly sensitive beyond 90 %RH, as shown in figure 6.10.

Figure 6.10 Response curve of gelatin-coated LPG shows that the LPG’s resonance dip is highly sensitive at RH beyond 90%RH. The resonance wavelength was stable around 1536.7nm.

6.4.2.1 SENSITIVITY

Figure 6.11 Figure shows the response of the gelatin-coated LPG RH sensor’s to region of high humidity.

The response of the gelatin-coated LPG to RH in the region between 90 %RH and 99 %RH is shown in figure 6.11. It can be observed that the sensor exhibits a near linear response, with a linear fit having a regression fit of 0.9983. The sensor’s sensitivity was calculated to yield 0.833 %RH/dBm. A non-systematic test was carried out by breathing straight into the sensor, its response was observed to change within seconds. The resolution of the sensor is limited by the measurement system, in this case the OSA. The OSA can measure optical intensity to a minimum step of 0.01 dB with an error of ± 0.3 dB. With this, the LPG RH sensor resolution and accuracy was calculated to be ± 0.01 %RH and ± 0.3 %RH respectively. LPGs are known to be highly sensitive to small changes in the refractive index, and as small as $\Delta n \sim 6 \times 10^{-5}$ [117]. Thus the resolution of the LPG RH sensor is limited by the calibration systems.

Another test was also conducted to investigate the response of the LPG which is coated with PVA instead of gelatin. Experimental results show a very erratic pattern, which is non-linear as compared with gelatin-coated LPG, as shown in figure 6.12. This could be due to the uneven coating of PVA on the LPG. During the preparation process, unlike gelatin, it is found that PVA is not able to adhere well to the fiber as small bumps of PVA coating can be observed after the dehydration process. Hence this might explain the erratic results shown in figure 6.12.

From the results, it can be seen that as RH increases from 70 %RH, the coupling strength of the transmission dip starts to increase but at a slower pace. Beyond 85 %RH this rate increased but at 95 %RH there is a turning point, in which the coupling strength decreases. Such response is not desired as a single reading obtained from the PVA-coated LPG can represent two RH values, for example 80 %RH and 100 %RH reading, which may lead to misinterpretation of the results. In dry places like Canada, it may not be much of a problem as the RH does not normally go beyond 80 %RH. Problem will arise if PVA-coated LPG is used in countries in Southeast Asia such as Singapore, where this test is conducted.

Figure 6.12 Figure shows the response curve of the PVA-coated LPG RH sensor.

6.4.2.2 REPEATABILITY AND HYSTERESIS

Figure 6.13 Repeatability test shows that the response of the gelatin-coated LPG RH is highly repeatable.

In the repeatability and hysteresis characterization process, the gelatin-coated LPG sensor was subjected to 3 cycles of RH test. In each test, the sensor was first subjected to a stepwise increase of RH, followed by the reverse process, after reaching 99 %RH. Figure 6.13 shows that the response of the gelatin-coated LPG RH sensor is repeatable. The LPG RH sensor exhibits a repeatability of 99.71 %, which corresponds to a repeatability error of ± 0.877 %RH. A more accurate measurement of RH is not possible as the size of the humidity chamber presents some problems like the humidity fluctuations and uneven humidity distribution. Therefore, if a more accurate humidity calibration chamber is used, the gelatin-coated LPG RH sensor may achieve a much greater repeatability, higher than 99.71 %.

Figure 6.14 Figure shows the results from hysteresis test.

In any sensor, hysteresis has to be looked into as it determines the accuracy of the sensor. The response of the gelatin-coated LPG sensor for one cycle of RH test is shown in figure 6.14. It can be observed from the sensor's response that the gelatin-

coated LPG exhibits small hysteresis. Using the same data that was used for the calculation of repeatability, the hysteresis of the gelatin-coated LPG was calculated to be ± 0.203 %RH. In comparison, the typical hysteresis of commercial relative humidity sensors is rated at ± 1 %RH, which makes the hysteresis error of the gelatin-coated LPG RH sensor five times smaller than the conventional ones.

6.4.2.3 STABILITY

Figure 6.15 Stability test of the gelatin-coated LPG RH sensor produced a stability error of ± 0.05 %RH, under a constant humidity of 95 %RH and temperature of 25 °C.

Figure 6.15 illustrates the results obtained from the sensor stability test. The test was carried out in an airtight container containing a salt solution that yields constant RH of 95 %RH. The temperature throughout the test period was kept constant at 25 °C. The response of the sensor was monitored every 10 mins for 260 mins. It can be observed, from figure 6.15, that the LPG RH sensor response fluctuates with time but these fluctuations are small. These small fluctuations giving an approximate RH

error of 0.04 % could be due to a combination of errors from the monitoring instruments used in the measurements. With stability error of 0.04 %RH, it can be calculated that the output from the gelatin-coated LPG RH sensor is stable with time.

6.5

OPTIMIZING SENSITIVITY

To improve the sensor’s sensitivity, two factors come into play. One is the gelatin’s concentration while the other factor is the optical property of the LPG. In the investigation of LPG sensitivity to gelatin concentration, three LPGs were used. Although all the LPGs were of the same grating period of 450μm, each of them received different concentrations of gelatin coating, 5 %, 10 % and 20 %. Same coating procedure was applied to all three LPGs so as to minimize thickness variations between them. The results are shown in figure 6.16.

Figure 6.16 Results show that as gelatin concentration increases the sensor sensitivity decreases.

Figure 6.16 shows that the sensor loses its sensitivity as the gelatin concentration increases in the coating. At 10 % gelatin concentration, the sensor's sensitivity decreases from 0.8 %RH/dBm (5 % gelatin concentration), to 0.23 %RH/dB. This is approximately three times lower than the LPG coated with 10 % gelatin concentration. At 20 % gelatin concentration, the response of the sensor became erratic, rendering the sensor useless. A probable explanation for the degradation of the LPG sensor with higher gelatin concentration is that the gelatin area near to the gelatin/air interface could have readily absorbed the water vapor from the atmosphere even at low RH forming a saturation layer that prevents the gelatin molecules at the gelatin/cladding interface from reacting to the atmosphere RH. This is graphically illustrated in figure 6.17. Thus the change in the gelatin's optical property is small at the gelatin/cladding interface. As the interaction with the cladding mode occurs at the interface region, the small optical property changes of the gelatin will render the sensor less sensitive as shown in test result in figure 6.16.

Figure 6.17 Pictorial illustration of the penetration depth of water vapor into gelatin layer for different gelatin concentration.

The experiments described above so far investigates the effect of the external medium on the sensor’s sensitivity. The second factor, which affects the sensor’s performance, is the order of LPG cladding modes used. To obtain different order of cladding modes and having them fall within the optical communication window of 1520 nm to 1620 nm, amplitude mask of various periodicities have to be used. In addition to existing 300 μm LPG, two LPGs with different grating periods, 450 μm and 550 μm , were fabricated for this purpose. All three LPGs were coated with the same gelatin concentration of 5 % concentration, and were subject to the same high RH testing sequence. Experimental results from these gelatin-coated LPGs RH sensors are plotted against relative humidity as shown in figure 6.18.

Figure 6.18 Graph shows the sensitivity of the gelatin-coated LPG sensor to RH for different cladding mode order.

The cladding mode order, with resonance wavelength within the optical communication window, for the 300 μm , 450 μm and 550 μm LPGs are 7th, 5th and 3rd

respectively. From the figure 6.18, all three gelatin-coated LPGs exhibit similar response to high relative humidity. It is obvious from the figure that the gelatin-coated LPG's sensitivity is an incremental function of cladding mode order. The LPG with a grating period of 300 μm exhibits the highest sensitivity of 0.8 %RH/dBm.

The reason for such a trend is as follows. Each of the cladding modes of the LPG can be characterized by rays whose angle, with respect to the fiber normal, decreases with the increasing cladding mode order (m). For the same refractive index of the external medium, the lower order cladding modes have well confined modal power [54]. Thus they have less interaction with the external medium. As the order of the cladding mode increases, a larger portion of the modal field interacts with the external medium. This leads to the LPG spectrum being more sensitive to change in refractive index of the external medium. From the LPG characteristic curve (figure 2.17) a larger number of higher cladding modes can be obtained from smaller grating periods. Hence the gelatin-coated LPG RH sensor sensitivity can be greatly enhanced by careful selection of the grating periods. By fabricating the LPGs such that the cladding modes fall within the optical communications windows, one is able to take advantage of using optical components which are readily available and economical. This helps to reduce system cost and down time if any part of the optical components has to be replaced due to faulty components.

All sensors, electrical or optical, will be affected by temperature change. Due to its temperature sensitivity, LPG has been used for temperature measurements. However, temperature changes can also cause drift in the final output reading of the sensor. Therefore in this section, we will investigate the response of temperature change on the gelatin-coated LPG RH sensor. The 300 μm LPG was placed in the

climate control chamber with the relative humidity held constant and temperature ramped from 15 °C to 35 °C. Results were taken and plotted as shown in figure 6.19.

Figure 6.19 The graph shows that change in temperature causes changes in output of the gelatin-coated LPG RH sensor.

Figure 6.19 depicts the fluctuations of output readings from the sensor with temperature change. It can be observed that the fluctuations of readings under different relative humidity follow a similar trend. These fluctuations can be attributed to two main contributors, namely the intrinsic and extrinsic contributors. The intrinsic contribution comes from the LPG itself, and the extrinsic contribution comes from gelatin coating and the relative humidity. As the LPG is sensitive to temperature changes, a change in temperature will result in a change in the grating coupling strength [60]. Experimental test was conducted and it was found that the changes in the gratings coupling strength of a bare LPG is very small as compare to the change due to change of relative humidity, in figure 6.20.

Figure 6.20 Test results show small reduction of coupling strength of a bare LPG with temperature.

The second factor is the gelatin coating itself. Polymer has a natural characteristic that it will change its refractive index with different temperature. This characteristic had been exploited for used as a temperature compensation technique in an LPG [101]. However in the case of gelatin, we were not able to verify this as there is another factor, which affects the refractive index of the gelatin coating, which is the relative humidity. It is known that relative humidity will vary with the air temperature. Generally, the relative humidity varies inversely with air temperature such that the relative humidity is highest when the temperature is lowest, and vice versa.

As the whole experiment was conducted over a period of 3 months, we were able to investigate degradation on the sensor over time. Results were collected and plotted as shown in figure 6.21.

Figure 6.21 A comparison plot shows sensor response after fabrication and 3 months later.

From figure 6.21, it shows that there is a certain amount of degradation in the sensor itself. Despite the degradation, the sensor is still able to maintain its high repeatability and low hysteresis error. As the LPG itself has a long lifespan, the main cause of this degradation is the gelatin coating itself. Since gelatin is an organic material, there will be a high chance of growth of mould, thus affecting the life span of the sensor. One possible recommendation is to use polyethylene oxide as it will not be subjected to mould growth. However polyethylene oxide is easily damaged by immersion in water and a search for another alternative will be necessary. For this project, the choice of gelatin is due to its low cost and availability. Below is a summary of the pros and cons of gelatin-coated LPG RH sensor.

STRONG POINTS

- Able to measure high humidity (90 %RH – 100 %RH) without condensation on the surface of the sensor.
- Highly repeatable results with low hysteresis even if the sensor performance has degraded.
- Can easily be demodulated using cost effective photodetection systems.
- Can be easily integrated into existing optical communication systems or networks as the LPG and the optical components are all fabricated to operate within the optical communication region.
- Low cost.

DOWNSIDE

- Sensor shows signs of degradation after 3 months, which is due to mould growth on the gelatin surface.
- LPG is sensitive to bending loss but can be overcome by ensuring that the LPG remains straight during packaging.

During the experiment, measurements were carried out with both ends of the optical fiber, one for light source and one for the OSA. This could be a hassle during an actual industrial application and thus a probe-based system will be able to alleviate this hassle. One method of improvement is to use the LPG-based Michelson Interference technique [118]. This technique uses a single-probe Michelson interferometer that employs mode coupling in a long-period grating to establish the two optical paths in a single optical fiber. The interferometer phase shift depends on the refractive index of the material that surrounds the fiber probe, with the phase

sensitivity directly proportional to the probe length. The advantage of single probe sensor enables easier and quicker installation of such sensors in difficult to access locations. To use this configuration for RH sensing, the RH sensitive coating material must be able to expand with RH so that this expansion can create the change in the optical path difference.

In summary, the use of gelatin-coated LPG as a high relative humidity sensor has been demonstrated. Gelatin was used as the coating agent due to its ability to vary its refractive index with RH. Instead of wavelength shift, the resonance cladding mode dip, representing the loss or coupling strength, changes with varying average refractive index of the gelatin coating. From the experiment, gelatin was found to be highly sensitive in the region of high humidity, between 90 and 99 %RH. From the experimental investigations, the gelatin-coated LPG RH sensor exhibits a sensitivity of 0.8 %RH with a resolution of ± 0.01 %RH and accuracy of ± 0.3 %RH. In the hysteresis, repeatability and stability investigations, the sensor exhibited a hysteresis error of ± 0.203 %RH, a repeatability of 99.71 % and corresponding to error of less than ± 0.9 %RH, and a stability error of less than ± 0.04 %RH. Another experiment to investigate the dependency of sensor sensitivity with different cladding mode order was carried out. Results demonstrated that the LPG humidity sensor's sensitivity increases at higher cladding mode order. Owing to many advantages of the optical fiber, sensitivity of LPG and characteristics of gelatin, the gelatin-coated LPG RH sensor can be used in areas where high humidity measurements are required and in harsh environments where present electrical type RH sensors are less suitable.

CHAPTER 7: Conclusion and Recommendations

At present, most LPG sensors developed are wavelength-based optical fiber sensors, where the effect due to the measurands is translated into wavelength changes. To interrogate these sensors would require expensive and complicated interrogation system such as an optical spectrum analyzer. In addition, other perturbations such as temperature and strain will affect the outcome of the results as these perturbations affect the LPG resonance wavelength too. The purpose of this work is to investigate the properties of LPG for sensing applications where the output of the LPG sensor is intensity-based, which requires less costly and complicated interrogation system such as photodetector.

Two LPG sensors were developed, which are intensity-based. An embedded LPG (ELPG) sensor was developed to measure the bending curvature of a structure to which the sensor is adhered to. It was experimentally found that bending the ELPG results in a change in the ELPG resonance dip or the coupling strength of the cladding mode while its resonance wavelength remains unchanged. An explanation was proposed suggesting that bending of ELPG reduced the reflected cladding mode energy and shifted the cladding mode's field profile. As a result of the reduction in overlap between the energy of the fundamental core mode and the reduced energy of the shifted cladding mode, the coupling strength decreased. This affects the LPG's resonance dip. Experimental characterization showed that the sensor exhibits linear sensitivity of 5.065 dB/m^{-1} with an accuracy of 0.01 m^{-1} in curvature. From the repeatability and hysteresis tests, the results obtained were highly repeatable, showing a 98.1 % repeatability, and with a hysteresis error of 0.051 dB or 0.02 m^{-1} in curvature.

In additional, the ELPG has also been demonstrated for its capability to detect bending direction, which is an added advantage.

Although the main purpose of ELPG bending sensor is for bending sensing, the unique ELPG response to bending enables a new type of application in the area of optical communications. In this application, the ELPG had been experimentally demonstrated to dynamically equalize the EDFA's gain spectrum, giving a uniform gain for different pump current of the EDFA. This is made possible by controlling the depth of the ELPG resonance dip, through tuning of the ELPG's curvature, which matches that of the peak of the EDFA gain spectrum.

In the second sensor, a gelatin-coated LPG high relative-humidity (RH) sensor has been developed and demonstrated for high RH sensing, which addresses current problems associated with conventional electrical-based humidity sensor. It was found that the changes in RH, in between 90 %RH and 99 %RH, affect the resonance dip or coupling strength of the gelatin-coated LPG. This could be due to the hydrophilic nature of the thin gelatin coating. LPG spectrum is sensitive to changes of refractive index of the external surrounding medium and readings from the LPG spectrum suggested that the gelatin refractive index is close to that of the cladding's refractive index such that a small change in the gelatin refractive index will create a large response in the LPG resonance dip but a small change in the resonance wavelength.

Characterization of the gelatin-coated LPG RH sensor shows that the sensor's response to humidity is near-linear, and the sensor's sensitivity was calculated to be 0.8 %RH/dBm. From five cycles of repeatability and hysteresis test, the sensor shows

a repeatability of 99.71 % and hysteresis error of 0.203 %RH. From the stability test, under a constant RH of 95 % for a period of 260 mins, the results from the sensor remain relative stable with a stability error of 0.04 %RH. To study the factors affecting the sensitivity of the sensor, investigations on the sensor's response to coating concentration as well as the order of cladding mode were also carried out. Results show that the sensor's performance degrades at higher gelatin coating concentration and at a lower cladding mode. One limitation of the gelatin-coated LPG sensor is its inability to compensate for temperature fluctuation. Although the experimental results had shown no significant effect on the un-coated LPG due to temperature change, there might have an effect on the gelatin coating itself. In addition, temperature change will also affect the relative humidity, which is beyond our control.

From all these sensors developed, it was found that the LPG's transmission characteristics can be greatly affected by the external medium's refractive index surrounding the LPG and also the concentration of this medium. This resulted in a change of LPG characteristic from wavelength-based sensor to intensity-based sensor. Understanding the optical properties of LPG allows one to optimize the sensor's performance, like in the case of gelatin-coated LPG high relative humidity sensor. When using the LPG for communications, recoating the LPG to protect it may cause undesirable consequences. This however provides opportunity to use it as a sensor to solve present problems.

Recommendations for future work

To further improve the LPG sensors developed, several suggestions are listed as follows;

- **Theoretical work on the embedded long period grating bending sensor**

Although theoretical modeling of the long period grating under bending has been published, the condition is not the same as that of the embedded LPG. It is based on bare optical fiber where the surrounding medium is air. In an embedded LPG, the surrounding medium is no longer air and its refractive index is higher than that of cladding. Hence to achieve a clearer understanding on the phenomenon exhibited by the embedded LPG under bending, a theoretical study is therefore suggested. This study can be a topic by itself.

- **Compensation for temperature fluctuation in gelatin-coated long period grating high relative-humidity sensor**

A change in temperature not only changes the relative humidity in the atmosphere, it has slight effects on the peak loss of the resonance dip in the LPG spectrum. Therefore for any result obtained, it contains information about both relative humidity and temperature. One recommendation is to fabricate a LPG such that the material contribution and waveguide contribution due to temperature cancel out each other as discussed in chapter 2. With that, a temperature independent LPG can be achieved.

- **Solving moulding problem with gelatin-coated long period grating relative-humidity sensor**

From the experimental data, there is an observable change of degradation of the gelatin coating itself. Since gelatin is an organic material, it will be subjected to mould growth and thus affecting the life span of the sensor. One possible recommendation is to use polyethylene oxide as it would not be subjected to mould growth. However, polyethylene is easily damaged by immersion in liquid water. Another type of possible coating for the LPG is porous sol-gel due to the advantages of the ability to control the porosity and its high resistance to high temperature. This makes the sensor more versatile for operation in applications working in harsh environment conditions. Therefore future work in investigating a more suitable coating to replace gelatin is suggested.

REFERENCES

1. Eric Udd, "Fiber Optic Sensors-An Introduction for Engineers and Scientists", John Wiley & Sons, Inc., 1991.
2. <http://physics.nad.ru/sensors/English/interf.htm>.
3. Wolfgang Ecke, Ines Latka, Reinhardt Willsch, Arnd Reutlinger and Roland Graue, "Fibre optic sensor network for spacecraft health monitoring," *Meas. Sci. Technol.*, **12**, pp. 974–980, 2001.
4. Kin-tak Lau, Chi-chiu Chan, Li-min Zhou, Wei Jin, "Strain monitoring in composite-strengthened concrete structures using optical fibre sensors," *Composites: Part B*, **32**, pp. 33–45, 2001.
5. C. Fernandez-Valdivielso, I.R. Matias, F.J. Arregui, "Simultaneous measurement of strain and temperature using a fiber Bragg grating and a thermochromic material," *Sensors and Actuators A*, **101**, pp. 107–116, 2002.
6. P. Chojnowski and K. P. Jedrzejewski, "Strain sensor applications of fiber Bragg gratings," *Proceedings of SPIE Vol.* **5948**, 2005.
7. W. Liang, Y. Huang, Y. Xu, R. K. Lee, and A. Yariv, "Highly sensitive fiber Bragg grating refractive index sensors," *Applied Physics Letters*, **86**, pp. 1-3, 2005.
8. Jun Cong, Xianmin Zhang, Kangsheng Chen, Jian Xu, "Fiber optic Bragg grating sensor based on hydrogels for measuring salinity," *Sensors and Actuators B*, **87**, pp. 487–490, 2002.
9. A. Trouillet, E. Marin, C. Veillas, and H. Gagnaire, "Optical fibre sensors for hydrogen leak detection," presented at 2005 AIChE Spring National Meeting, Conference Proceedings, 2005.
10. Wei Liang, Yanyi Huang, Yong Xu, Reginald K. Lee, and Amnon Yariv, "Highly sensitive fiber Bragg grating refractive index sensors", *Appl. Phys. Lett.*, **86**, 151122 (3 pages), 2005.
11. A. Iadicicco, A. Cusano, A. Cutolo, R. Bernini, and M. Giordano, "Thinned fiber Bragg gratings as high sensitivity refractive index sensor," *IEEE Photonics Technology Letters*, **16**, pp. 1149-1151, 2004.
12. <http://www.bryair.com/library.htm>, "Humidity, It's Effect On Electronic Industry And Solutions".
13. http://www.findarticles.com/p/articles/mi_m0EEH/is_1_29/ai_n9484992, "An overview of the effect of moisture on compaction and compression: the effects of moisture on the flow properties, tensile strength, Heckel plot, energies involved in compaction, and elastic recovery are reviewed".

14. D.G. Fredlund and H. Rahardjo, Chapter 4, "Soil Mechanics for Unsaturated Soils", John Wiley and Sons Ltd., New York, 1993.
15. Bernard M. Kulwicki, "Humidity Sensors", J. Am. Ceram. Soc., **74**, pp. 697-708, 1991.
16. G.J.W. Visscher and J.G. Kornet, "Long term tests of capacitive humidity sensors", Measurement Science and Technology, **5**, pp. 1294-1302, 1994.
17. H. J. Patrick, C. C. Chang and S. T. Vohra, "Long period fiber gratings for structural bend sensing," Electronics Letters, **34**, pp 1773-1775, 1998.
18. D A Gonzalez, JL Arce-Diego, A cobo and J M Lopez-Higuera, "Spectral modeling of curved long-period fibre gratings," Meas. Sci. Technol., **12**, pp 786-792, 2001.
19. Y. Liu, L. Zhang, J. A. R. Williams, and I. Bennion, "Optical Bend Sensor Based on Measurement of Resonance Mode Splitting of Long-Period Fiber Grating," IEEE Photon. Technol. Lett., **12**, pp 531-533, 2000.
20. D. Zhao, X. Chen, K. Zhou, L. Zhang, I. Bennlon, W. N. MacPherson, J. S. Barton, and J. D. C. Jones, "Bend sensors with direction recognition based on long-period gratings written in D-shaped fiber," Applied Optics, **43**, pp. 5425-5428, 2004.
21. T. Allsop, M. Dubov, A. Martinez, F. Floreani, I. Khrushchev, D. J. Webb, and I. Bennion, "Long period grating directional bend sensor based on asymmetric index modification of cladding," Electronics Letters, **41**, pp. 59-60, 2005.
22. S. Chen, Z. Tong, Q. Zhao, Z. Liu, and X. Dong, "A smart bending sensor with a novel temperature- and strain-insensitive long-period grating," Sensors and Actuators, A: Physical, **116**, pp. 103-106, 2004.
23. Kamil Sokolowski, Andrzej W. Domanski, and Tomasz R. Wolinski, "Intensity-based Fiber Optic Bend Sensor for Potential Railway Application," Proceedings of SPIE Vol. 5484, pp. 417-420, 2004.
24. Y.Yu, Z. Zhao, Z. Zhuo, W. Zheng, Y. Qian, and Y. Zhang, "Bend sensor using an embedded etched fiber Bragg grating," Microwave and Optical Technology Lett., **43**, pp. 414-417, 2004.
25. Y.J. Rao, T. Zhu, Z.L. Ran, Y.P. Wang, J. Jiang and A.Z. Hu, "Novel long-period fiber gratings written by high-frequency CO₂ laser pulses and applications in optical fiber communication," Optics Communications, **229**, pp. 209-221, 2004.
26. G. D. VanWiggeren, T. K. Gaylord, D. D. Davis, M. I. Braiwish, Elias N. Glytsis, and E. Anemogiannis, "Tuning, attenuating, and switching by controlled flexure of long-period fiber gratings," Optics Letters, **26**, pp. 61-63, 2001.

27. K. Ogawa, S. Tsuchiya, H. Kawakami and T. Tsutsui, "Humidity-sensing effects of optical fibers with microporous SiO₂ cladding," *Electronic Letters*, **24**, pp. 42-43, 1988.
28. Sunil K. Khijwania, Kirthi L. Srinivasan and Jagdish P. Singh, "An evanescent-wave optical fiber relative humidity sensor with enhanced sensitivity," *Sensors and Actuators B: Chemical*, **104**, pp. 217-222, 2005.
29. R. Jindal, S. Tao, J. P. Singh, and P. S. Gaikwad, "High dynamic range fiber optic relative humidity sensor," *Optical Engineering*, **41**, pp. 1093-1096, 2002.
30. C. M. Tay, K. M. Tan, S. C. Tjin, C. C. Chan, and H. Rahardjo, "Humidity sensing using plastic optical fiber," *Microwave and Optical Technology Lett.*, **43**, pp. 387-390, 2004.
31. Shinzo Muto, Osamu Suzuki, Takashi Amano and Masayuki Morisawa, "A plastic optical fiber sensor for real-time humidity monitoring," *Meas. Sci. Technol.*, **14**, pp. 746-750, 2003.
32. D. C. Bownass, J. S. Barton, and J. D. C. Jones, "Detection of high humidity by optical fibre sensing at telecommunications wavelengths," *Optics Communications*, **146**, pp. 90-94, 1998.
33. A. Gaston, I. Lozano, F. Perez, F. Auza, and J. Sevilla, "Evanescent wave optical-fiber sensing (temperature, relative humidity, and pH sensors)," *IEEE Sensors Journal*, vol. 3, pp. 806-811, 2003.
34. S. Luo, Y. Liu, A. Sucheta, M. Evans and R. V. Tassell, "Applications of LPG fiber optical sensors for relative humidity and chemical warfare agents monitoring," *Proceedings of SPIE Vol. 4290*, pp. 193-204, 2002.
35. Y.J. Rao, A.Z. Hu, Y.C. Niu, "A novel dynamic LPFG gain equalizer written in a bend-insensitive fiber," *Optics Communications*, **244**, pp. 137-140, 2005.
36. B. D. Gupta and Ratnanjali, "A novel probe for a fiber optic humidity sensor," *Sensors and Actuators, B: Chemical*, **80**, pp. 132-135, 2001.
37. P. Kronenberg, P. K. Rastogi, P. Giaccari, and H. G. Limberger, "Relative humidity sensor with optical fiber Bragg gratings," *Optics Letters*, **27**, pp. 1385-1387, 2002.
38. A MacLean, W Craig Michie, S G Pierce, G Thursby, B Cuishaw, C Moran and N B Graham, "Hydrogel/Fibre Optic Sensor for Distributed Measurement of Humidity and pH Value", *SPIE vol. 3330*, pp. 134-144, 1998.
39. Gerd Keiser, "Optical Fiber Communications", McGraw Hill, 2000, sec. 2.3.2.
40. A. M. Vengsarkar, P. J. Lemaire, J. B. Judkins, V. Bhatia, J. E. Spie, and T. E. Ergodan, "Long-period fiber gratings as band-rejection filters", *J. of Lightwave Technol.*, **14**, pp. 58, 1996.

41. M. Born and E. Wolf, "Principle of Optics", New York: Pergamon, 1987, sec. 8.6.1, eq. (8).
42. H. F. Taylor and A. Yariv, "Guide wave optics", Proceedings of the IEEE, **62**, pp. 1044, 1974.
43. F. Bilodean, K.O. Hill, B. Malo, D. Johnson, and I. Skinner, "Efficient narrowband $LP_{01} \leftrightarrow LP_{02}$ mode convertors fabricated in photosensitive fiber: Spectral response", Elect. Lett., **27**, pp 682-684, 1991.
44. K. O. Hill, Y. Fuji, D. C. Johnson, and B. S. Kawasaki, "Photosensitivity in optical fiber waveguides: Application to reflection fiber fabrication", App. Phys. Lett., **32**, pp 647-649, 1978.
45. Andreas Othonos, Kyriacos Kalli, "Fiber Bragg Gratings: Fundamentals and Applications in Telecommunications and Sensing", Artech House, 1999.
46. A. D. Kersey *et al.*, "Fiber grating sensors", IEEE Journal of Lightwave Technol., **15**, pp 1442-1463, 1997.
47. Meltz G., and W. W. Morey, "Bragg grating formation and germanosilicate fiber photosensitivity", International Workshop on Photoinduced Self-Organization Effects in Optical Fiber, Quebec City.
48. A. Iadicicco, A. Cusano, A. Cutolo, R. Bernini, and M. Giordano, "Thinned Fiber Bragg Gratings as High Sensitivity Refractive Index Sensor", IEEE Photon. Technol. Lett., **16**, pp. 1149-1151, 2004.
49. Kerstin Schroeder, Wolfgang Ecke, Rudolf Mueller, Reinhardt Willsch and Andrey Andreev, "A fibre Bragg grating refractometer", Meas. Sci. Technol. **12**, pp. 757-764, 2001.
50. Wei Liang, Yanyi Huang, Yong Xu, Reginald K. Lee, and Amnon Yariv, "Highly sensitive fiber Bragg grating refractive index sensors", Appl. Phys. Lett., **86**, 151122 (3 pages), 2005.
51. T. W. MacDougall, S. Pilevar, C. W. Haggans, and M. A. Jackson, "Generalized Expression for the Growth of Long Period Gratings," IEEE Phot. Technol. Lett., **10**, pp. 1449-1451, 1998.
52. S. A. Vasiliev *et al.*, "Properties of cladding modes of an optical fibre excited by refractive index gratings", Russian J. of Quantum Elect., **29**, pp 65-68, 1999.
53. A. Cherin, "An Introduction to Optical Fibers", McGraw-Hill, Singapore, 1989.
54. V. Bhatia, "Properties and sensing applications of long-period gratings," Ph.D. Thesis, Virginia Tech. Blacksburg, VA, 1996.

-
55. J. W. Fleming, "Material dispersion in lightguide glasses", *Electron. Lett.*, **14**, pp. 326-327, 1978.
 56. N. P. Bansal and R. H. Doremus, "Handbook of Glass Properties", Academic Press, Florida, 1986.
 57. M. J. Adams, "An Introduction to Optical Waveguides", Wiley-Interscience, New York, 1981.
 58. Xuewen Shu, Lin Zhang and ian Bennion, "Sensitivity Characteristics of Long-Period fiber Gratings", *IEEE Journal of Lightwave Technol.*, **20**, pp 255-266, 2002.
 59. Bai-Ou Guan, Hwa-Yaw Tam, Helen LW Chan, Chung-Loong Choy and Muhtesem Suleyman Demokan, "Growth characteristics of long-period gratings in hydrogen-loaded fibre during and after 193nm UV inscription", *Meas. Sci. Technol.*, **12**, pp 818–823, 2001.
 60. Mei Nar Ng and Kin Seng Chiang, "Thermal effects on the transmission spectra of long-period fiber gratings", *Opt. Comms.*, **208**, pp 321–327, 2002.
 61. Heather J. Patrick, Alan D. Kersey and Frank Bucholtz, "Analysis of the Response of Long Period Fiber Gratings to External Index of Refraction", *IEEE J. of Lightwave Technol.*, **16**, pp 1606-1612, 1998.
 62. A. W. Snyder and J. D. Love, "Optical waveguide theory", Chapman and Hall, London, 1984.
 63. T. Erdogan, "Fibre grating spectra," *IEEE J. Lightwave Technol.*, **15**, pp. 1277-1294, 1997.
 64. Vikram Bhatia, "Applications of long-period gratings to single and multi-parameter sensing", *Opt. Express*, **4**, pp. 457–466, 1999.
 65. Stephen W James and Ralph P Tatam, "Optical fibre long-period grating sensors: characteristics and application", *Meas. Sci. Technol.* **14**, pp. 49–61, 2003.
 66. Shu X, Allsop T, Gwandu B, Zhang L and Bennion I, "High temperature sensitivity of long-period gratings in B–Ge codoped fibre", *IEEE Photon. Technol. Lett.*, **13**, pp. 818–820, 2001.
 67. Heather J. Patrick, Alan D. Kersey and Frank Bucholtz, "Analysis of the Response of Long Period Fiber Gratings to External Index of Refraction", *IEEE J. of Lightwave Technol.*, **16**, pp 1606-1612, 1998.
 68. R Hou, Z Ghassemlooy, A Hassan, C Lu and K P Dowker, "Modelling of long-period fibre grating response to refractive index higher than that of cladding", *Meas. Sci. Technol.*, **12**, pp. 1709–1713, 2001.

-
69. Olivier Duhem, Jean-Francois Henninot, Marc Warenghem, and Marc Douay, "Demonstration of long-period-grating efficient couplings with an external medium of a refractive index higher than that of silica", *Appl. Opt.*, **37**, pp. 7223-7228, 1998.
 70. H. J. Patrick, C. G. Askins, R. W. McElhanon, and E. J. Friebele, "Amplitude mask patterned on an excimer laser mirror for high intensity writing of long period fibre gratings," *Electronics Lett.*, **33**, pp. 1167-1168, 1997.
 71. D. D. Davis, T. K. Gaglord, E. N. Glytsis, S. G. Kosinski, S. C. Mettler, and A. M. Vengsarkar, "Long-period fibre fabrication with focused CO₂ laser pulses", *Electronics Lett.*, **34**, pp. 302-303, 1998.
 72. Yuki Kondo, Kentaro Nouchi, Tsuneo Mitsuyu, Masaru Watanabe, Peter G. Kazansky, Kazuyuki Hirao, "Fabrication of long-period fiber gratings by focused irradiation of infrared femtosecond laser pulses", *Optics Lett.*, **24**, pp. 646-648, 1999.
 73. G. Rego, O. Okhotnikov, E. Dianov, and V. Sulimov, "High-Temperature Stability of Long-Period Fiber Gratings Produced Using an Electric Arc", *Journal of Lightwave Technol.*, **19**, pp. 1574-1579, 2001.
 74. C. Y. Lin and L. A. Wang, "A wavelength- and loss-tunable band-rejection filter based on corrugated long-period fiber grating," *IEEE Photonics Technology Lett.*, **13**, pp. 332-334, 2001.
 75. B. E. A. Saleh and M. C. Teich, "Fundamental of Photonics", John Wiley, New York, 1991.
 76. Hill K. O., Fuji Y., Johnson D. C., and Kawasaki B. S., "Photosensitivity in optical waveguides: Application to reflection filter fabrication", *Applied Physics Lett.*, **32**, pp. 647-649, 1978.
 77. P. J. Lemaire, R. M. Atkins, V. Mizrahi, and W. A. Reed, "High-pressure H₂ loading as a technique for achieving ultrahigh UV photosensitivity and thermal sensitivity in GeO₂ doped optical fibres", *Electronics Lett.*, **29**, pp. 1191-1193, 1993.
 78. William D. L., Ainslie B. J., Armitage J. R., Kashyap R., and Campbell R. J., "Enhanced UV photosensitivity in boron codoped germanosilicate optical fibres", *Electronics Lett.*, **29**, pp. 45-47, 1993.
 79. F. Bilodeau, R. Malo, J. Albert, D. C. Johnson, K. O. Hill, Y. Hibino, M. Abe, and M. Kawachi, "Photosensitization of optical fiber and silica-on-silicon/silica waveguides," *Optics Lett.*, **18**, pp. 953-955, 1993.
 80. E. Salik, D. S. Starodubov, V. Grubsky, and J. Feinberg, "Increase of photosensitivity in Ge-doped fibres under strain", *Optical Fibre Communication Conference (OFC2000)*, paper TuH5, 2000.

81. G.D. VanWiggeren, T.K. Gaylord, D.D. Davis, E. Anemogiannis, B.D. Garrett, M.I. Braiwish, E.N. Glytsis, "Axial rotation dependence of resonances in curved CO₂-laser-induced long-period fibre gratings", *Electronics Lett.*, **36**, pp 1354-1355, 2000.
82. Hyung Suk Ryu, Yongwoo Park, Seong Tae Oh, Youngjoo Chung, and Dug Young Kim, "Effect of asymmetric stress relaxation on the polarization-dependent transmission characteristics of a CO₂ laser-written long-period fiber grating", *Optics Lett.*, **28**, pp 155-157, 2003.
83. O. Duhem and M. Douay, "Effect of UV-induced birefringence on long period-grating coupling characteristics", *Electronic Lett.*, **36**, pp. 416-417, 2000.
84. Brent L. Bachim and Thomas K. Gaylord, "Polarization-dependent loss and birefringence in long-period fiber gratings", *Appl. opt.*, **42**, pp. 6816-6823, 2003.
85. Y.J. Rao, T. Zhu, Z.L. Ran, Y.P. Wang, J. Jiang, A.Z. Hu, "Novel long-period fiber gratings written by high-frequency CO₂ laser pulses and applications in optical fiber communication", *Optical Communications*, **229**, pp 209–221, 2004.
86. Yun-Jiang Rao, Yi-Ping Wang, Zeng-Ling Ran, and Tao Zhu, "Novel Fiber-Optic Sensors Based on Long-Period Fiber Gratings Written by High-Frequency CO₂ Laser Pulses", *Journal of Lightwave Technology*, **21**, pp. 1320-1327, 2003.
87. C. Caucheteur, A. Fotiadi, P. Mégret, S. A. Slattery, and D. N. Nikogosyan, "Polarization Properties of Long-Period Gratings Prepared by High-Intensity Femtosecond 352-nm Pulses", *IEEE Photonics Technology Lett.*, **17**, pp. 2346-2348, 2005.
88. L A Wang, C Y Lin and G W Chern, "A torsion sensor made of a corrugated long period fibre grating", *Measurement Science and Technology*, **12**, pp 793–799, 2001.
89. Bai-Ou Guan, Hwa-Yaw Tam, Helen L W Chan, Chung-Loong Choy and Muhtesem Suleyman Demokan, "Growth characteristics of long-period gratings in hydrogen-loaded fibre during and after 193nm UV inscription", *Measurement Science and Technology*, **12**, pp 818-823, 2001.
90. Malo B, Albert J, Hill K O, Bilodeau F and Johnson D C, "Effective index drift from molecular hydrogen diffusion in hydrogen-loaded optical fibres and its effect on Bragg grating fabrication", *Electronics Lett.*, **30**, pp 442–443, 1994.
91. Hiroyuki Kawano, Holger Muentz, Yukio Sato, Junichi Nishimae, and Atsushi Sugitatsu, "Reduction of Transmission Spectrum Shift of Long-Period Fiber Gratings by a UV-Preexposure Method", *Journal of Lightwave Technology*, **19**, pp. 1221-1228, 2001.

92. T. Ergodan, V. Mizrahi, P. J. Lemaire, and D. Monroe, "Decay of ultra-violet-induced fiber Bragg gratings", *Journal of Applied Physics*, **76**, pp. 73-80, 1994.
93. Tjin, S.C., Hao, J.Z., Malik, R., "Fiber optic pressure sensor using a fiber Bragg grating", *Proceedings of SPIE* vol. 3429, pp. 123-130, 1998.
94. Y. Wang, S. C. Tjin, J-Z Flao, T. K. Lim, K. B. Tan, K. M. Chan, "Determination of Load-Strain Characteristics of Concrete Slabs by Using Embedded Fiber Bragg Grating Sensors", *Proceedings of SPIE* vol. 4073, pp. 297-304, 2000.
95. R.M.Gill, "Carbon fiber in composite materials", London Iliffe Books, 1972.
96. <http://www.hexcel.com/NR/rdonlyres/230A6C2A-FDFA-4EC7-B048-E4EB28E3BC8C/0/PrepregTechnology2.pdf> (2005).
97. Hao Jianzhong, "Design and Fabrication of a Fiber Optic Pressure Sensor", Doctoral Thesis, School of Electrical and Electronic Engineering, Singapore, 2000.
98. S. Ramachandran, J. Wagener, R. Espindola, and T. A. Strasser, "Effects of chirp in long period gratings," in *Bragg Gratings, Photosensitivity, and Poling in Glass Waveguides*, T. Erdogan, E. Friebele, and R. Kashyap, eds., Vol. 33 of OSA Trends in Optics and Photonics Series (Optical Society of America, 1999), paper BE1.
99. V. Bhatia, D. K. Campbell, D. Sherr, T. G. D'Alberto, N. A. Zabaronick, G. A. Ten Eyck, K. A. Murphy, and R. O. Claus, "Temperature-insensitive and strain-insensitive long-period grating sensors for smart structures," *Optical Engineering*, **36**, pp. 1872-1875, 1997.
100. K. Shima, K. Himeno, T. Sakai, S. Okude, A. Wada, and R. Yamauchi, "Novel temperature-insensitive long-period fiber grating using a boron-codoped-germanosilicate-core fiber," *Conference on Optical Fiber Communication, Technical Digest Series*, pp. 347-348, 1997.
101. J.-N. Jang, S. Y. Kim, S.-W. Kim, and M.-S. Kim, "Temperature insensitive long-period fibre gratings," *Electronics Lett.*, **35**, pp. 2134-2136, 1999.
102. C. C. Ye, S. W. James and R. P. Tatam, "Simultaneous temperature and bend sensing with long-period fiber gratings," *Optics Lett.*, **25**, pp 1007-1009, 2000.
103. M. G. Xu, J. L. Archambault, L. Reekie and J. P. Dakin, "Discrimination between strain and temperature effects using dual-wavelength fibre grating sensors," *Electronics Lett.*, **30**, pp 1085-1087, 1994.

104. C. C. Chan, C. Z. Shi, W. Jin and D. N. Wang, "Improving the Wavelength Detection Accuracy of FBG Sensors Using an ADALINE Network," *IEEE Photonics Technology Lett.*, **15**, pp. 1126-1128, 2003
105. J.E. Ford and J.A. Walker, "Dynamic spectral power equalization using micro-opto-mechanics," *IEEE Photonic Technology Lett.*, **10**, pp. 1440-1442, 1998.
106. H.S. Kim, S.H. Yun, H.K. Kim, N. Park and B.Y. Kim, "Actively gain-flattened erbium-doped fiber amplifier over 35nm by using all fiber acousto-optic tunable filters," *IEEE Photonics Technology Lett.* **10**, pp. 790-792, 1998.
107. B.J. Offrein, F. Horst, G.L. Bona, R. Germann, H.W.M. Salemink, R. Beyeler, "Adaptive gain equalizer in high-index-contrast SiON technology," *IEEE Photonics Technology Lett.* **12**, pp. 504-506, 2000.
108. Pieter L. Swart, Thabiso J. Nhlapo and Anatoli A. Chitchebakov, "Long-period grating filter with tunable attenuation for spectral equalization of erbium-doped fiber broadband light sources," *Optical Eng.*, **43**, pp. 280-281, 2004.
109. Enboa Wu, Rou-Ching Yang, Kuo-Ching San, Chien_hung Lin, Fares Alhassen and H. P. Lee, "A Highly Efficient Thermally Controlled Loss-Tunable Long-Period Fiber Grating on Corrugated Metal Substrate," *IEEE Photonics Technology Lett.*, **17**, pp. 612-614, 2005.
110. Ainhua Gaston, Fatima Perez, and Joaquin Sevilla, "Optical Fiber Relative-Humidity Sensor with Polyvinyl Alcohol Film," *Applied Optics*, **43**, pp. 4127-4132, 2004.
111. A. P. Russell and K. S. Fletcher, "Optical sensor for the determination of moisture," *Anal. Chim. Acta*, **170**, pp 209-216, 1985.
112. Nicholas D. Rees, Stephen W. James and Ralph P. Tatam, "Optical fiber long-period gratings with Langmuir-Blodgett thin-film overlays," *Optics Lett.*, **27**, pp 686-688, 2002.
113. Ignacio Del. Villar et al., "Deposition of overlays by electrostatic self-assembly in long-period fiber gratings", *Opt. Lett.*, vol, 30, pp. 720-722, 2005.
114. A. Cusano et al., "Mode transition in high refractive index coated long period gratings", *Opt. Express*, vol. 14, pp. 19-34, 2006.3
115. Zhiyong Wang et al., "Analysis of optical response of long period fiber gratings to nm-thick thin-film coatings", *Opt. Express*, vol. 13, pp. 2808-2813, 2005.

116. Ignacio Del Villar, Ignacio R. Matías and Francisco J. Arregui, "Optimization of sensitivity in Long Period Fiber Gratings with overlay deposition", *Opt. Express*, **13**, pp. 56-69, 2004
117. T. Allsop, L. Zhang, I. Bennion, "Detection of organic aromatic compounds in paraffin by a long-period fiber grating optical sensor with optimized sensitivity," *Optics Communications*, **191**, pp. 181-190, 2001.
118. Pieter L Swart, "Long-period grating Michelson refractometric sensor", *Meas. Sci. Technol.*, **15** (2004), pp 1576–1580.