

FIBER BRAGG GRATING SENSORS FOR pH AND
HUMIDITY MEASUREMENT

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To

My parents, my husband and my children

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ABSTRACT

pH sensor and humidity sensor have received much attention since their application is of great importance in many fields. Due to their advantages, optical fiber sensors have been introduced and investigated to overcome the limitation of conventional pH and humidity sensors. However, there are some drawbacks, such as low sensitivity, low accuracy and low multiplexing capability of the current optical sensors. This thesis presents the design and development of new optical fiber sensors for pH and humidity measurement by adopting fiber Bragg grating (FBG) technique. Three types of sensor design which are hydrogel coated-unetched FBGs, hydrogel coated-etched FBGs and elastomer-hydrogel coated FBGs are proposed for pH measurement. FBG based-Fabry-perot (FBG-FP) was proposed as humidity sensor with temperature compensation. The coating thickness on the cavity is higher than that on the FBGs to obtain different humidity response and temperature response. The working principle of both FBG pH sensors and humidity sensors relies on stress induced on the fiber due to mechanical expansion of swelling sensing materials coated on the FBG. The swelling sensing material used to construct FBG pH sensors is pH sensitive hydrogel synthesised by Hydroxyethyl Methacrylate (HEMA), acrylic acid and ethylene glycol dimethacrylate as crosslinker. Meanwhile, the swelling sensing material used to construct FBG humidity sensors is polyimide. Optimisation of the FBG pH sensors was done by analysing the strain induced in the FBG due to swelling of the coating material. The swelling of pH sensitive hydrogel was modeled using free energy function and was solved using finite element method by adopting ABAQUS software. Theoretical analysis of the FBG-FP response to humidity and temperature change was done using coupled mode theory. For FBG-FP humidity sensor, calculation results show that the humidity sensitivity and thermal sensitivity are 1.92pm/%RH and 8.87pm/°C, respectively, for polyimide coating thickness of 10µm on the FBG and 15µm on the cavity. Fabrications were done for both pH sensor and humidity sensor. For pH sensor, hydrogel coated-etched FBG with hydrogel coating thickness of 90µm and etched fiber diameter of 40µm was fabricated and characterised. Results indicate that the sensor has a good reversibility and provides linear response in pH range of 4.97 to 7.17 with sensitivity of 0.056nm/pH unit and 0.195nm/pH unit at pH of 4.97 and 7.17, respectively. For FBG-FP humidity sensor with recoated diameter of 145µm on the FBG and 157µm on the cavity, the experimental results show that the humidity sensitivity and thermal sensitivity are 1.75×10^{-3} nm/%RH and 1.52×10^{-2} nm/°C, respectively.

ABSTRAK

Sensor pH dan sensor kelembapan telah menerima banyak perhatian kerana penggunaannya adalah amat penting dalam pelbagai bidang. Sensor gentian optik telah diperkenalkan dan dikaji untuk mengatasi had daripada sensor pH dan sensor kelembapan konvensional. Tetapi, sensor optik semasa memiliki beberapa kelemahan seperti sensitiviti rendah, ketepatan yang rendah dan keupayaan pemultipleksan rendah. Tesis ini membentangkan reka bentuk dan pembangunan sensor gentian optik yang baru bagi pengukuran pH dan kelembapan dengan menggunakan teknik gentian parutan Bragg (FBG). Tiga jenis reka bentuk sensor iaitu FBG bersalut hidrogel-tanpa ukir, FBG bersalut hidrogel-terukir, dan FBG bersalut hidrogel elastomer dicadangkan untuk pengukuran pH. FBG berasaskan Fabry-Perot (FBG-FP) telah dicadangkan sebagai sensor kelembapan dengan pampasan suhu. Ketebalan salutan pada rongga adalah lebih tinggi berbanding di FBGs untuk mendapatkan tindak balas RH yang berbeza dan tindak balas suhu. Prinsip kerja bagi kedua-dua sensor pH dan sensor kelembapan bergantung kepada tekanan yang dikenakan kepada gentian disebabkan pengembangan mekanikal dari bahan penderiaan pengembangan yang disalut pada FBG. Bahan penderiaan pengembangan yang digunakan untuk membina sensor pH FBG adalah hidrogel peka pH disintesis dari Hidroksil Metakrilat (HEMA), asid akrilik dan etilena glikol dimetakrilat sebagai *crosslinker*. Sementara itu, bahan penderiaan pengembangan yang diguna bagi membina sensor kelembapan FBG adalah *polyimide*. Pengoptimuman sensor pH FBG telah dilakukan dengan menganalisis tekanan yang dikenakan dalam FBG disebabkan pengembangan bahan salutan. Pengembangan peka pH telah dimodelkan menggunakan fungsi tenaga bebas dan telah diselesaikan melalui kaedah unsur terhingga dengan menggunakan perisian ABAQUS. Analisis teori tindak balas FBG-FP terhadap kelembapan dan perubahan suhu telah dilakukan menggunakan teori mod berganding. Untuk sensor kelembapan FBG-FP, keputusan pengiraan menunjukkan bahawa kepekaan RH adalah $1.92\text{pm}/\%RH$ dan kepekaan haba adalah $8.87\text{pm}/^{\circ}C$, bagi ketebalan salutan *polyimide* $10\mu\text{m}$ pada FBG dan $15\mu\text{m}$ pada rongga. Fabrikasi telah dilakukan untuk kedua-dua sensor pH dan sensor kelembapan. Bagi sensor pH, FBG bersalut hidrogel-terukir dengan ketebalan lapisan hidrogel $90\mu\text{m}$ dan diameter gentian terukir $40\mu\text{m}$ telah difabrikasi dan dicirikan. Keputusan menunjukkan bahawa sensor mempunyai kebolehbalikan yang baik dan memberikan tindak balas linear dalam julat pH bermula 4.97 sehingga 7.17 dengan kepekaan unit $0.056\text{nm}/\text{pH}$ pada pH 4.97 dan kepekaan unit $0.195\text{nm}/\text{pH}$ pada pH 7.17. Bagi sensor kelembapan FBG-FP dengan diameter salutan $145\mu\text{m}$ pada FBG dan $157\mu\text{m}$ pada rongga, keputusan ujikaji menunjukkan bahawa kepekaan kelembapan adalah $1.75 \times 10^{-3}\text{nm}/\%RH$ dan sensitiviti haba adalah $1.52 \times 10^{-2}\text{nm}/^{\circ}C$.

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LIST OF SYMBOLS

d_ρ	-	Dispersion
f_x^e	-	Element nodal forcing parameter
A^-	-	Conjugate bases
a_{eff}	-	Apodization factor
A_f	-	Cross sectional area of fiber
AH	-	Acidic groups
A_p	-	Cross sectional area of polyimide coating
B_f	-	Body force
c	-	Speed of light in vacuum
c_-	-	True concentration of co-ion in the gel
C_+	-	Nominal concentration of counter-ion
c_+	-	True concentration of counter ion in gel
c_k^0	-	Concentration of the k^{th} ion in stress-free state
C_{A^-}	-	Nominal fixed charges
C_{AH}	-	Nominal concentration of acidic group
c_f	-	Concentration of fixed charge in hydrogel
c_{H^+}	-	True concentration of hydrogen ions H^+ within hydrogel.
C_{H^+}	-	Nominal concentration of proton
C_{ijkl}	-	Elastic modulus tensor
c_k	-	Concentration of the k^{th} ionic species inside hydrogel
c_+^{ref}	-	Reference true concentration counter-ion
$c_{H^+}^{ref}$	-	Reference true concentration of proton
c_{mo}^s	-	Total concentration of acidic groups in dry gel
c_w	-	Water concentration
D	-	Diffusion coefficient

d	-	Cavity length of Fabry-perot interferometer
D_{etch}	-	Etched fiber diameter
DetF	-	Swelling ratio
D_t	-	Matrix determinant
E	-	Young's modulus
ϵ_0	-	Dielectric constant of vacuum
E_s	-	Shear modulus under infinitesimal straining
ϵ_s	-	Relative dielectric constant of solvent
F	-	Faraday constant
f	-	Number of acidic groups attached to the network divided by the total number of monomers in the network
$f(z)$	-	Apodization profile
F_{iK}	-	Deformation gradient
F_x	-	External forces
H	-	Local hydration of hydrogel
H^+	-	Hydrogen ions
I_f	-	Interpolation function
I_{p1}	-	Intensity of peak 1 of FBG-FP spectrum
I_{p2}	-	Intensity of peak 2 of FBG-FP spectrum
K	-	Grating wavevector
K	-	Global stiffness matrix
K_ϵ	-	Sensitivity of FBG to strain
K_a	-	Dissociation constant of the carboxylic acid groups
k^e	-	Element stiffness
k_f	-	Radiation wavevector
k_i	-	Incident wavevector
K_{RH1}	-	RH sensitivity for the center wavelength of FBG-FP spectrum peak
K_{RH2}	-	RH sensitivity for the normalized intensity M
K_T	-	Sensitivity of FBG to temperature
K_{T1}	-	Thermal sensitivity for the center wavelength of FBG-FP spectrum peak

K_{T2}	-	Thermal sensitivity for the normalized intensity M
L	-	Grating length
L_c	-	Length of unbuffered region
L_m	-	Lame's coefficient of the solid matrix
M	-	Normalized parameter of peak intensity
m_a	-	Mass of dry air
m_w	-	Mass of water vapor
N	-	Number of polymer chains divided by the volume of the dry network
n_-	-	Numbers of particles of co-ions
n_+	-	Numbers of particles of counter ions
n_{eff}	-	Effective refractive index of the fiber in the absence of grating
n_{H^+}	-	Numbers of particles of hydrogen ions
n_s	-	Numbers of particles of solvent molecules
P_e	-	Effective photoelastic coefficient
P_{ij}	-	Pockel's (piezo) coefficients
P_s	-	Saturated water vapor pressure
P_w	-	Partial pressure of water vapor
r	-	Power reflectivity
R	-	Universal gas constant
$R(z)$	-	Forward going-wave
R_{FP}	-	Power reflectivity of Fabry-perot interferometer
r_{max}	-	Maximum reflection
$S(z)$	-	Backward going-wave
S_{ijkl}	-	Elastic compliance tensor
T	-	Transfer matrix
T	-	Temperature
t_c	-	Complex amplitude of the transmission coefficient
t_d	-	Diffusion time
T_{elt}	-	Elastomer coating thickness
t_{FP}	-	Complex amplitude coefficient of the transmitted spectrum of Fabry-perot interferometer

T_{hyd}	-	Hydrogel thickness
T_r	-	Traction
u	-	Displacement of the deformed materials
v	-	Volume per monomer
V_f	-	Fluid volume
V_{net}	-	Volume of dry air
V_s	-	Solid volume
V_t	-	Total volume of hydrogel
W	-	Free-energy density of gel
W_{dis}	-	Free-energy density due to dissociating the acidic groups
W_{ion}	-	Free-energy density due to mixing ions with the solvent
W_{net}	-	Free-energy density due to stretching networks
W_{sol}	-	Free-energy density due to mixing the solvent with the network
X	-	Coordinate of reference state
x	-	Coordinate of current state
z_f	-	Valency of fixed charge in hydrogel
z_k	-	Valency of the k^{th} ion
$\bar{\delta}n_{eff}$	-	Refractive index modulation peak
\bar{E}_t	-	Transverse component of the electric field along grating
$\bar{e}_{jt}(x, y)$	-	Cladding modes
$\hat{\sigma}$	-	dc self coupling coefficient
τ_ρ	-	Delay time
$\{\zeta\}$	-	Unknown nodal values
$\{\Xi\}$	-	Column vector of the unknown variables
\bar{c}_{H^+}	-	True concentration of hydrogen ions in the external solution
\bar{c}_+	-	True concentration of counter-ion in the external solution

\bar{c}_-	-	True concentration of co-ion in the external solution
ℓ	-	Principal stretch ratio
ν	-	Fringe visibility of the index change
Λ	-	Grating period
β	-	Propagation constant
ω	-	Angular frequency
κ	-	ac coupling coefficient
ρ	-	Complex amplitude reflection coefficient of FBG
ρ_{FP}	-	Complex amplitude coefficient of the reflected spectrum of Fabry-perot interferometer
ξ	-	Thermo-optic coefficient
α	-	Thermal expansion coefficient
ν	-	Poisson's ratio
σ	-	Stress
ψ	-	Electric potential
Π	-	Osmotic pressure
χ	-	Dimensionless parameter
γ	-	The increase in the enthalpy when an acidic group dissociates
η	-	Strain hardening exponent
ϕ	-	Phase delay of Fabry-perot interferometer
θ_ρ	-	Phase of the amplitude reflection coefficient
$\Delta\lambda_0$	-	Zero to zero-bandwidth
$\Delta\lambda_B$	-	Bragg wavelength shift
$\Delta\lambda_P$	-	Center wavelength shift of FBG-FP spectrum peak
$\phi(z)$	-	Grating chirp
λ_B	-	Bragg wavelength
Λ_g	-	Period of interference pattern of phase mask technique
δ_{ij}	-	Kronecker delta

Π_{ion}	-	Osmotic pressure due to the imbalance of the number of ions in the gel and in the external solution
Λ_{pm}	-	Period of the phase mask
ε_{pRH}	-	Strain on polyimide coating due to humidity change
ε_{pT}	-	Strain on polyimide coating due to temperature change
ε_{RH}	-	Strain on fiber induced by humidity change
v_S	-	Volume per solvent molecule
Π_{sol}	-	Osmotic pressure due to the mixing the network and the solvent
ε_T	-	Strain on fiber due to temperature change
λ_{UV}	-	Wavelength of the laser beam
δv	-	Virtual displacement field
ε_z	-	Axial strain
$\bar{\delta n}_{eff}(z)$	-	dc index change spatially averaged over a grating period
$[a_{H^+}]$	-	Hydrogen ion activity
$[H^+]$	-	Hydrogen ion concentration on solution
μ	-	Lame's coefficient of the solid matrix
μ_-	-	Electrochemical potentials of co-ions
μ_+	-	Electrochemical potentials of counter ions
μ_{H^+}	-	Electrochemical potentials of hydrogen ions
μ_s	-	Electrochemical potentials of solvent molecules
v	-	Volume per monomer
ε_x	-	Strain in x direction
ε_y	-	Strain in y direction

LIST OF ABBREVIATION

AA	-	Acrylic acid
BCG	-	Bromocresol green
BCP	-	Bromocresol purple
CME	-	Coefficient of moisture expansion
CTE	-	Thermal expansion coefficient
DMPA	-	2,2-dimethoxy-2-phenyl-acetophenone
EGDMA	-	Ethyleneglycol-dimethacrylate
EW	-	Evanescent wave
EWFS	-	Evanescent wave fiber optic sensor
FBG	-	Fiber Bragg grating
FBG-FP	-	Fiber grating Fabry–Perot interferometer
FEM	-	Finite element method
FP	-	Fabry–Perot interferometer
FWHM	-	Full width half maximum
HEMA	-	Hydroxyethyl methacrylate
LMRs	-	Lossy mode resonances
LPG	-	Long period grating
MECpH	-	Multi-effect coupling pH-stimulus
NR	-	Neutral Red
OSA	-	Optical spectrum analyzer
PAA	-	Poly(acrylic acid)
PAH	-	Poly(allylamine hydrochloride)
PDDA	-	Poly(diallyldimethylammonium)
PEO/CoCl ₂	-	Poly(ethylene oxide)-cobalt chloride
PMMA	-	Polymethylmethacrylate
PNP	-	Poisson-Nernst- Planck

PVA	-	Polyvinyl alcohol
RH	-	Relative humidity
SEM	-	Scanning electron microscope
SMF	-	Single mode fiber
SNR	-	Signal to noise ratio
SR	-	Silicon rubber
TCFMI	-	Thin-core fiber modal interferometer
TDM	-	Time domain multiplexing
UV	-	Ultraviolet
VB	-	Victoria blue
WDM	-	Wavelength-division multiplexing

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Routine measurements of chemical parameters are required in wide applications such as industrial production, environmental monitoring, biotechnology, medicine and agriculture. Among various types of chemical parameters, pH and humidity are of the most essential parameters since their measurement is of great importance in many fields.

The measurement of pH, a measure of the acidity or basicity of a solution, is one of the parameter used in environmental monitoring such as river water quality monitoring, seawater analysis, ground water analysis and wastewater monitoring. A lot of biological and geochemical processes occurring in freshwater, seawater and marine sediments involve strong pH changes (Kocincová, 2007). In water quality monitoring, pH is an important indicator since it determines whether the water is chemically changing or not. The change of river water's pH can harm animals and plants living in the water. In wastewater treatment, pH measurement is important to ensure that the treated wastewater is suitable for discharge back into the environment. The pH measurement is also essential in agriculture, food science, process control in industry, and clinical fields.

Whereas, humidity monitoring is a matter of concern in various areas such as environmental monitoring, agriculture, weather forecasting, and most importantly in

manufacturing factory of chemicals, food products and electronic components where air-conditioning control is crucial to ensure good production process. In manufacturing process, moisture in the atmosphere must be controlled below a certain level. Textiles, papers and cereals must be dried to a standard storage condition in order to prevent the quality deterioration.

Conventional sensors have been widely used for long time such as electronic meters (glass electrode) (Ballance, 1996) for pH measurement and capacitance sensors (Matsuguchi et al., 1998; Roman et al., 1995) for humidity sensors. However, conventional sensors suffer from several drawbacks such as relatively large size, not suitable to be used in hazardous environment and not possible for distributed and multiplexed sensing system.

Optical sensors have been introduced and investigated recently to overcome the limitation of conventional pH sensors (Boisde et al., 1988; Grant et al., 2001; Jones & Porter, 1988; Leiner & Hartmann, 1993; Lin, 2000; Mohr & Wolfbeis, 1994) and humidity sensors (Akita et al., 2010; Itagaki et al., 2009; Wu et al., 2011). The advantages of optical sensors are freedom from electromagnetic interference, wide bandwidth, compactness, geometric versatility, feasibility of miniaturization, and possibility of remote sensing and real time measurement. Optical sensors also offer a possibility of deployment of distributed and array sensors covering extensive structures and geographical locations with low power loss. In addition, by multiplexing fiber sensors, the cost per sensing point can be reduced and the connection of the network can be simplified.

In general, based on modulation technique, optical sensor can be classified as an intensity, a phase, a frequency, a polarization sensor and a wavelength sensor. Wavelength modulated sensor is attractive since the measurand information is wavelength encoded, i.e., the sensed information is encoded directly into wavelength, which is an absolute parameter. Therefore, the output signal of wavelength sensor does not depend on the input light level and losses along the optical system. The most widely used wavelength based sensor is Fiber Bragg grating (FBG) sensor due to its superior multiplexing capability. The FBGs can be multiplexed on a single

optical fiber which allows the measurement of measurand at different places on a large structure to be relatively easily implemented. Utilization of FBG for sensor application is done by taking the advantage of the dependence of the grating parameter to temperature and strain. Due to the dependence of the grating parameter to temperature and strain, the Bragg wavelength of an FBG can be tuned by applying strain or temperature. FBG-based sensors make use of the shift of the Bragg wavelength with respect to the sensing parameter. The primary interest of FBG sensor applications is for strain and temperature measurement (Iadicicco et al., 2006; Kerrouche et al., 2008; Rao et al., 2000). However, FBG sensors are also useful for other applications such as chemical sensors, pressure sensors, and accelerometers. Due to the above-mentioned attractive properties, FBG technique is a potential candidate to be used in the development of pH and humidity sensors with compact structure, high accuracy, high sensitivity and high multiplexing capability.

1.2 Sensor Performance Parameters

Performance of a sensor is defined by several parameters as follow:

1. Sensitivity

Sensitivity of a sensor is defined as the change in output of the sensor per unit change in the parameter being measured. The factor may be constant over the range of the sensor (linear), or it may vary (nonlinear).

2. Linearity

The most convenient sensor to use is one with a linear transfer function. That is an output that is directly proportional to input over its entire range, so that the slope of a graph of output versus input describes a straight line.

3. Accuracy

The accuracy of the sensor is the maximum difference that will exist between the actual value, which is measured by a good standard, and the indicated value at the output of the sensor. Generally, the accuracy represents the largest expected error between actual and ideal output signals.

4. Range

The range of the sensor is the maximum and minimum values of applied parameter that can be measured. It represents the highest possible input value which can be applied to the sensor without causing unacceptably large inaccuracy. Applied parameters outside of this range are expected to cause unacceptably large inaccuracy.

5. Reversibility and Hysteresis

Reversibility measures the capability of a sensor to follow the changes of the input parameter regardless of which direction the change is made. In opposite, hysteresis determines the characteristic that a sensor has in being unable to repeat reversely the measurement results that have been recorded in one direction.

6. Repeatability

Repeatability represents the ability of a sensor to repeat a measurement when put back in the same environment. It is specified by the maximum difference between different measurements when the same procedure is repeated under the same condition. Repeatability is often directly related to accuracy, but a sensor can be inaccurate, yet be repeatable in making observations.

7. Response Time

Response time is defined as the time required for a sensor to change the output from its previous state to 90% of a new final value.

1.3 Problem Statement

Most of the current optical pH sensor and optical humidity sensors are intrinsic fiber optic sensor based on spectroscopic methods. Spectroscopic method can be realized by applying absorption and fluorescence method. An attractive feature of absorption method is that it is simple and easy to use. However, it has drawback in term of sensitivity. Also, the absorption method require thick sensing layer and is difficult to miniaturize (Lin, 2000).

Other phenomenon such as evanescent wave (EW) has also been used to develop pH and humidity sensors. EW fiber optic sensor (EWFS) exploits the

optical absorption at the core-cladding interface of the fiber optic. EWFS uses measurand sensitive dye which is immobilized on the uncladded portion of an optical fiber (Gupta & Sharma, 1997). However, measurement with the above-mentioned technique suffer from instabilities resulting from decrease in the concentration of indicator due to leaching and photobleaching (Lin, 2000). Moreover, since the methods are optical intensity modulated, measurement is highly affected by fluctuations in the intensity of light source and variations in light attenuation through the optical fiber due to changes in the degree of bending. Thus, measurement errors may occur.

FBG technique can be adopted to overcome the accuracy limitation of the current optical pH sensors. In designing FBG sensor, it is important to ensure that the Bragg wavelength shift per unit of the parameter being measured (sensitivity) is large enough to be resolved by FBG interrogation system. Most of the FBG interrogation system currently available in the market provides wavelength resolution of $\sim 1\text{pm}$. Since the sensing principle of FBG pH sensors relies on mechanical effect induced on the fiber, the sensitivity can be improved by increasing the induced mechanical response. However, the increase of mechanical response means the increase of stresses on the fiber. Therefore, optimization should be made by considering trade-off between sensitivity and physical reliability.

Triques and co-workers have developed FBG-based pH sensor with sensitivity of $\sim 0.094\text{nm/pH unit}$ (Junior et al., 2007; Triques et al., 2006). However, the design is bulky, complex and not suitable to be multiplexed on a single optical fiber, hence limits the multiplexing capability. Thus, there is a space to develop FBG-based pH sensor to obtain optical pH sensor with compact structure, high accuracy, high sensitivity and high multiplexing capability.

For humidity sensor application, even though the use of FBG has been studied by researchers (David et al., 2012; Huang et al., 2007; Iadicicco et al., 2006; Kronenberg et al., 2002; Yeo et al., 2005), temperature cross sensitivity as the main problem in FBG sensors still need further investigation to be solved.

1.4 Objective

The objective of this work is divided into:

- To improve the compactness, accuracy and sensitivity of pH sensor by means FBG technique.
- To design and model FBG based humidity sensor with temperature compensation.
- To develop FBG based pH sensor and humidity sensor devices for practical performance characterization.

1.5 Scope of Research

In order to realize the research objectives, the works to be carried out in this research have been identified as follow:

- Modeling and simulation of pH-sensitive hydrogel swelling behavior.
- Simulation of strain induced in the FBG due to the mechanical expansion of pH-sensitive hydrogel coating.
- Simulation and analysis the properties of FBG spectrum under the influence of hydrodynamic volume change of pH-sensitive hydrogel coating.
- Simulation and analysis the properties of FBG spectrum under the influence of hydrodynamic volume change of moisture sensitive coating material for humidity sensor application.
- Fabrication and characterization of the optimized FBG sensors.

1.6 Research Methodology

The first phase in the research methodology of this work is literature review to understand the problem, research requirement, and related current technology especially FBG sensor technology. Through the literature review, the related theory

and published works were overviewed. The findings were used to define the objectives, scopes, and design requirements for solving the problem of fiber optic sensor technology.

For FBG based pH sensor optimization, the first step is to choose the pH sensitive hydrogel to be used as coating material. The mechanical expansion of hydrogel coating due to pH change was modeled by investigating the swelling behavior of pH using numerical method. Then, the induced strain in the FBG due to mechanical expansion of hydrogel coating was simulated using finite element method (FEM) to find the optimum coating dimension. The wavelength shift of the FBG due to the induced strain was then calculated analytically to determine the sensor sensitivity to the pH change. The optimum design (grating length, coating thickness and fiber diameter) was then obtained from the simulation results.

Optimization of FBG based humidity sensor was done by design the sensor structure so that the sensor can serve as humidity and temperature simultaneously. To investigate the sensor response to humidity and temperature, spectral profile of the sensor due to the induced strain resulted from volume expansion of the moisture sensitive coating material was simulated by employing commercial software MATLAB.

Sensor performances of both FBG based pH sensor and FBG based humidity sensor which include reversibility, repeatability, accuracy and temperature response were then measured to investigate the device characteristics. The fabrications of the devices were done by outsourcing. The flowchart of the research methodology is depicted in Figure 1.1.

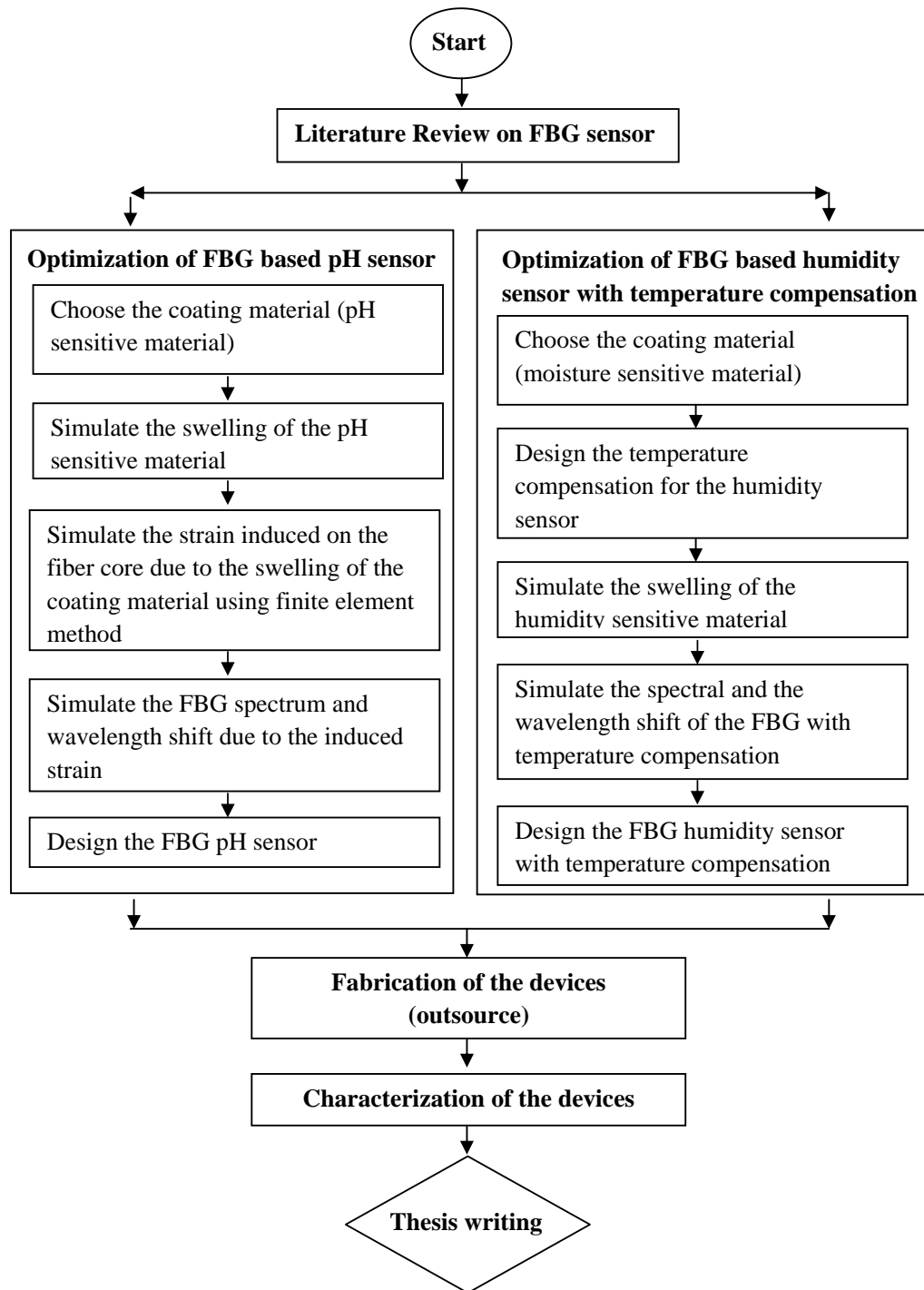


Figure 1.1 Flowchart of research methodology

1.7 Thesis Organization

This thesis is organized into 6 chapters. The importance of pH and humidity measurement has been discussed as introduction in Chapter 1. The problems and drawbacks of the existing optical sensors have been highlighted as problems to be solved in this work. The objective and the scope of the work are identified and presented.

Theoretical review of FBG is briefly elucidated in Chapter 2. The review started with discussion about FBG structure and principles of FBG, optical properties of FBG and is continued with the coupled mode theory that governs wave propagation in gratings. Solution to the coupled mode theory for uniform gratings and non uniform grating are presented. To gain knowledge about FBG fabrication, various FBG fabrication techniques are presented. Apodization technique to eliminate sidelobe in FBG spectrum is also discussed.

Chapter 3 discusses the sensing principle of FBG sensor and FBG chemical sensor. Various optical sensor techniques for pH and humidity measurement are briefly reviewed and compared. The constitutive model that relates the stress and strain induced on the optical fiber is presented. Since the FBG chemical sensor relies on the use of swelling sensing material to make the FBG sensitive to chemical measurands, theory that model the behavior of the coating materials is discussed. The cross sensitivity of FBG sensors and the technique to resolve it is also presented briefly.

Simulation and optimization of FBG sensor for pH and humidity measurement are discussed in Chapter 4. Design optimization of FBG pH sensor was done by analyzing the hydrogel swelling behavior, stress and strain on the fiber, and the Bragg wavelength shift due to temperature change. The simulation was done for three hydrogel coated FBG designs, namely hydrogel coated-unetched FBG, hydrogel coated-etched FBG, and hydrogel-elastomer coated FBG. Optimization of temperature compensated FBG humidity sensor is also presented in this chapter.

In Chapter 5, fabrication and characterization of the fabricated devices are presented. The characterization includes reversibility, repeatability, accuracy, time response and temperature response of the sensor.

Finally in Chapter 6, concluding remarks, contributions and recommendations for future prospects for this work are given.

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