DEVELOPMENT OF FIBRE INTERFEROMETER SENSORS BASED ON DOUBLE CLADDING FIBRE FOR MULTI-PARAMETER SENSING

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DEDICATION

For Mak and Abah

couldn't have done it without you

and to my beloved siblings,

Mek, Dee, Abg Tih, Abg D, Mashitoh, Fiqah, Balqis, and Iman.

Thank you for du'a and support throughout this entire journey.

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ABSTRACT

The role of sensors in the future industrial environment is becoming more crucial and complex. One of the important sensor characteristics is the multi-parameter sensing capability. Fibre interferometer is a type of optical sensor that has been proven for its excellent sensing performance, high design flexibility and high capability for multi-parameter sensing. This research work assesses the potential use of double cladding fibre (DCF) as an interferometric multi-parameter sensor. In light of the importance of multi-parameter sensing capability required in future industry environment, three novel sensor designs were proposed and experimentally demonstrated. These proposed designs incorporated DCF as the main sensor structure to maintain high commonality, as well as to fully utilize the unique sensing properties of DCF. The first design proposed in this study is the fibre Michelson interferometer based on DCF, which is used for refractive index (RI) and temperature sensing. This sensor operates based on two sensing mechanisms to detect RI and temperature. RI sensing relies on Fresnel reflection at the tip of DCF, whereby RI change is quantified from power change in the sensor spectrum. Meanwhile, temperature sensing depends on the interference between the core mode and the first cladding modes of DCF. Thermo-optic effect causes a change of wavelength in the sensor spectrum. The experimental results retrieved from the proposed sensor revealed that temperature and RI spectra responses were indeed distinguishable. The second design proposed in this study is the Mach-Zehnder interferometer with dual sensing points used for RI and discrete liquid level sensing. These two sections are separated by an RI insensitive region formed by the DCF section. The sensor can be utilised to measure RI in single- or dual-point configuration. The third design proposed in this study is the DCF-based Mach-Zehnder used for small curvature (or displacement) and large curvature (or circumference) sensing. In this proposed design, two optical paths are paved in the core and in the inner cladding of the DCF. The outer cladding of DCF provides confinement of light in the inner cladding, hence enabling higher curvature to be imposed without any significant optical loss. This research work covers conceptual sensor designs, sensor fabrication and experimentation work. At conceptual level, mathematical models of particular sensor structures were studied and further developed in order to understand the sensor behaviour. The particular sensor structures were analysed numerically using BeamProp software to understand its function from the field distribution. Systematic fabrication procedures were developed for the sensor to ensure high process efficiency and repeatability. Additionally, this thesis contributes to the development of experimentation setup and data acquisition process. The proposed multi-parameter sensors have great potential to be deployed in various industrial applications.

ABSTRAK

Peranan penderia dalam persekitaran industri masa hadapan menjadi semakin penting dan kompleks. Antara ciri penting penderia ialah kebolehan penderiaan pelbagai parameter. Gentian interferometer adalah sejenis penderia optik yang telah terbukti dengan prestasi penderiaan yang cemerlang, kefleksibelan reka bentuk yang tinggi dan berkemampuan tinggi untuk penderiaan pelbagai parameter. Kerja penyelidikan ini menilai potensi penggunaan gentian salut berganda (DCF) sebagai penderia interferometer pelbagai parameter. Mengambil berat mengenai pentingnya kemampuan penderiaan pelbagai parameter yang diperlukan dalam industri masa hadapan, tiga reka bentuk baru penderia telah diusulkan dan ditunjukkan secara eksperimen. Reka bentuk ini menggabungkan DCF sebagai struktur penderia utama untuk mengekalkan kesamaan yang tinggi dan juga memanfaatkan sepenuhnya sifat unik penderiaan DCF. Reka bentuk pertama yang dicadangkan dalam kajian ini adalah interferometer Michelson gentian berdasarkan DCF yang digunakan untuk penderiaan indeks biasan (RI) dan suhu. Penderia ini beroperasi menggunakan dua mekanisme penderiaan untuk mengesan RI dan suhu. Penderiaan RI bergantung pada pantulan Fresnel di hujung DCF, di mana perubahan RI dihitung dari perubahan kuasa dalam spektrum penderia. Sementara itu, penderiaan suhu bergantung pada interferens antara mod teras dan mod-mod salutan pertama DCF. Kesan termo-optik menyebabkan perubahan panjang gelombang dalam spektrum penderia. Hasil eksperimen yang diperolehi dari penderia yang dicadangkan menunjukkan bahawa tindak balas spektrum suhu dan RI dapat dibezakan. Reka bentuk kedua yang dicadangkan dalam kajian ini adalah interferometer Mach-Zehnder dengan dua titik penderia yang digunakan untuk penderiaan RI dan aras cecair diskret. Kedua-dua bahagian ini dipisahkan oleh kawasan tidak peka RI yang dibentuk oleh bahagian DCF. Penderia ini boleh digunakan untuk mengukur RI dalam tatarajah satu-titik dan dua-titik. Reka bentuk ketiga yang dicadangkan dalam kajian ini adalah Mach-Zehnder berteraskan DCF yang digunakan untuk penderiaan kelengkungan kecil (atau sesaran) dan kelengkungan besar (atau lilitan). Bagi reka bentuk yang dicadangkan ini, dua lintasan optik tersedia di dalam teras dan di bahagian salutan dalaman DCF. Salutan luaran DCF memberikan pengurungan cahaya pada salutan dalaman, sehingga membolehkan kelengkungan yang lebih besar dikenakan tanpa kehilangan optik yang ketara. Kerja penyelidikan ini merangkumi reka bentuk penderian konseptual, pemfabrikatan penderia dan kerja uji kaji. Pada aras konseptual, model matematik struktur penderia tertentu dikaji dan dibangunkan lebih lanjut untuk memahami kelakuan penderia. Struktur penderia tertentu juga dianalisis secara berangka mengunakan perisian BeamProp untuk memahami fungsinya dari taburan medan. Tatacara pemfabrikatan sistematik dikembangkan untuk penderia memastikan kecekapan proses dan keterulangan yang tinggi. Selain itu, tesis ini menyumbang kepada pembangunan persediaan uji kaji dan proses pemerolehan data. Penderia-penderia pelbagai parameter yang dicadangkan ini berpotensi tinggi untuk digunakan dalam pelbagai aplikasi industri.

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LIST OF ABBREVIATIONS

2D	-	Two dimensions
3FC	-	Three core fiber
CF	-	Coreless fiber
DCF	-	Double cladding fiber
ESMF	-	Etched single mode fiber
FBG	-	Fiber Bragg grating
FPI	-	Fabry-Perot interferometer
GPIB	-	General Purpose Interface Bus
HCPCF	-	Hollow core photonic crystal fiber
HF	-	Hydrofluoric Acid
HOF	-	Hollow core fiber
MI	-	Michelson interferometer
MMF	-	Multi-mode fiber
MZI	-	Mach-Zehnder interferometer
NCF	-	No core fiber
PCF	-	Photonic crystal fiber
PTFE	-	Polytetrafluoroethylene
RI	-	Refractive index
RIU	-	Refractive index unit
SI	-	Sagnac interferometer
SMF	-	Single mode fiber
TCF	-	Thin core fiber
TMSA	-	Three microspheres array
TOC	-	Thermo-optic coefficient

LIST OF SYMBOLS

x	-	Beam and platform length
R	-	Bent radius
n_{core}	-	Cladding layer
n	-	Core refractive index
κr	-	Curvature
D	-	Diameter
h	-	Displacement distance
L_{DCF}	-	Double cladding fiber length
L_{MMF}	-	Multi-mode fiber length
Δn_{neff}	-	Effective refractive index difference
v	-	Poisson's ratio
P	-	Power
r	-	Radius
ΔP	-	Relative power change
ΔP_{RI}	-	Relative power change of refractive index
ΔP_T	-	Relative power change of temperature
$\Delta\lambda$	-	Relative wavelength change
$\Delta\lambda_{RI}$	-	Relative wavelength changes of refractive index
$\Delta\lambda_T$	-	Relative wavelength changes of temperature
L_{SMF}	-	Single mode fiber length
L_0	-	Submerged interferometer length
T	-	Temperature
R^2	-	The coefficient of determination
α	-	Thermal expansion
λ	-	Wavelength

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CHAPTER 1

INTRODUCTION

1.1 Optical Fibre Sensor

Studies concerning optical fibre sensor that sparked in the 1960s [1] have witnessed substantial transformation after several decades of extensive research work. The role of optical fibre sensor technology complements the electronic counterpart in applications where electronic sensors perform marginally or do not exist. These main applications include oil and gas exploration [2,3], structural health monitoring [4–6], optical gyroscope [7], and military sonar [8–10]. Recently, optical fibre sensors have been studied across all fields. Fibre optic-based techniques, which provide the basis for sensor technology, produce sensors that are lightweight, small, easily multiplexable, and immune to electromagnetic interference (EMI). These sensors require no electrical power at the sensing point and have the potential to be produced at low cost. Performance and functionality of optical fibre sensor have been greatly improved with the continuous advancement of key components in fibre optic research domain, such as fabrication technique, digital signal processing, sensor materials, and specialty optical fibre. Some main fibre processing techniques, such as tapering, etching, laser micromachining, grating writing, and chemical deposition, have been extensively investigated. The accessibility to optical equipment and components is becoming easier because most of the components are available online at affordable price. Thus, the duration of product development starting from the initial concept stage to the prototype stage has been greatly shortened. Fibre optic sensors have been investigated for detection of physical parameters, such as temperature, strain, pressure, refractive index (RI), curvature, displacement, and acoustic, to name a few. The performance of optical fibre sensors, such as fibre Bragg grating (FBG), fibre multimode interference (MMI) devices, fibre interferometer, surface plasmon resonance (SPR), Brillouin/Raman scattering, and micro-structured fibres, has been substantially improved through the implementation of innovative techniques and modern technologies.

Various types of specialty optical fibres have been produced by manufacturers worldwide, including multicore fibre [11], double cladding fibre (DCF) [12], few mode fibre [13], coreless fibre [14], and photonic crystal fibre [15]. These fibres are incorporated into fibre sensor designs to utilise their distinctive sensing capabilities, which are absent in typical optical fibre such as single mode fibre (SMF) and multimode fibre (MMF). Previously, DCF is relatively unknown in sensing application. It possesses features of both SMF and MMF, thus allowing simultaneous transmission single mode and multimode. A DCF consists of a core, which is used for single mode transmission; an inner cladding (first cladding) used for multimode transmission, and an outer cladding layer (second cladding) that encapsulates the inner cladding, thus providing consistent surrounding RI.

Fibre interferometer sensor or interferometric sensor [16] is a type of optical sensors that have been proven for their high sensing performance and high design flexibility, which denote a growing technology. Fibre interferometer principles basically consist of three main mechanisms; (1) splitting of optical wave into two paths, (2) perturbations of measurands field on the sensing path, and (3) interference between optical wave in the sensing path and optical wave in the reference path. Implementation of DCF in interferometer construction deploys both the core and the first cladding as the two interferometer paths or arms. The interesting feature of DCF is that the first cladding is completely covered by the second cladding layer; hence there is no interaction with light through evanescent wave. The first cladding has better wave-guiding property than the cladding of conventional fibre, such as SMF. Hence, DCF has better control of the cladding modes over the surrounding environment, which could be useful in certain sensor designs.

Essentially, this study assesses the potential use of DCF in multi-parameter interferometric sensor, whereby multi-parameter sensing is one of the qualities required in the fourth industrial revolution. Three distinctive designs based on DCF are proposed in this thesis. The first design caters for temperature and RI sensing, which is crucial for several applications such as quality inspection in food manufacturing process and contamination detection in environmental monitoring. The second design is for RI and discrete liquid level sensing. This design is applicable for monitoring liquid quality and level in chemical storage. The third design is specifically used for displacement or curvature sensing. With the capability to measure small and large curvature, the sensor displays exceptional potential to be deployed in soft robotic, wearable medical device, and structural health monitoring applications. The prescribed sensing techniques contribute to the needs of the fourth industry revolution.

1.2 Problem Statement

The fourth industrial revolution is the latest shift of paradigm discussed throughout the academics and industries alike. It is basically a development in the manufacturing process to achieve mass production as effective as possible [17]. This is attainable through better control of the entire production process. Indeed, the role of sensors has increased substantially, mainly because the fourth industrial revolution emphasises on the use of high-performance sensors, smart sensors, high compatibility sensors, and multi-parameter sensors [18]. Multi-parameter sensing is defined as the capability of a sensor to detect or measure more than one parameter. In addition of enhanced functionalities, multi-parameter sensors also are capable to provide the information of the system state which important for anticipating influence of surrounding to measurement [19].

A number of multi-parameter fibre sensor structures have been developed using different fibre types and components [14,20–23] driven by the availability of various types of specialty optical fiber offered in the market. Performance-oriented [24–26] and functionality-oriented [27–30] design approaches have been widely practiced in most multi-parameter sensor design. The commonality or the standardized components used in different sensor structures have yet to be considered in the existing multi-parameter sensor designs. The vast selection of available optical fibres has promoted the use of various fibre combinations. However, in practice, it is crucial to maintain high commonality when developing different sensor structures as it reduces cost [31] and improves productivity by controlling the variation of components [32]. From this problem statement, this research work is motivated to study and develop multi-parameter sensor structures with high commonality. For this purpose, similar fibre components were deployed for 3 different sensor applications which are the SMF, MMF and DCF. Previously, DCF was used in high power fibre laser [33], multichannel data transmission [34] and imaging [35]. In this thesis, the unique properties of DCF are utilized for sensing purpose.

The first multi-parameter capabilities explored in this research work is combination of temperature and RI sensing. Information of surrounding temperature is important since many optical parameters are temperature dependent. For simultaneous temperature and RI sensing, several techniques have been deployed by researchers including interferometer structure written with FBG [36–38], capillary coated interferometer [39] and discrimination of different resonance dips [40,41]. These previous techniques involved with complex fabrication (FBG and capillary coating). This thesis proposes a novel and simple interferometer structure for simultaneous temperature and RI sensing based on DCF to overcome this limitation.

The second multi-parameter sensing capabilities studied in this research work is detection of both liquid level and RI. From literature review [42–44], there is very limited work related to development of sensor for simultaneous liquid level and RI sensing. The main reason is because of the difficulty to combine design requirements, whereby RI sensing requires a compact sensor head, while liquid level sensing requires extended physical coverage over the measured range. In order to fulfil both requirements, this thesis proposes a multi-point fibre interferometer sensor with both RI and discrete liquid level sensing capabilities.

This thesis also deals with small curvature (or displacement) and large curvature (or circumference) sensing. From literature review, it is found that there is lack of research work which focus on large curvature sensing especially in interferometer type sensor. Most of the designs are dealing with small curvature sensing [45,46]. Large curvature sensing requires very small bent radius of optical fiber. In typical fiber interferometer, the cladding modes may experience high radiation loss when small bending applied. To overcome the design issue, this thesis proposes an interferometer constructed using DCF. The use of DCF offered better confinement of the propagating modes in the inner cladding, thus realising a robust fibre curvature sensor.

This present study demonstrates the suitability of fibre interferometer sensor in this new industrial realm by focusing on the development of multi-parameter fibre optic sensors. By increasing sensor functionality through novel designs, this study explored into new application where the presence of fibre optical sensor is limited. Each sensing system component, including sensor head, fabrication process, data acquisition system, and sensing model, was thoroughly studied to unravel both existing issues and opportunities available.

1.3 Objectives

Based on the research motivations and problem statements listed above, the research objectives of this study are given in the following:

(a) To design new designs of fibre interferometer based on double cladding fibre for multi-parameter sensing.

(b) To carry out systematic fabrication procedure using in-house facilities.

(c) To evaluate sensors performance through experimental works, subsequently verify multi-parameter sensing capability.

1.4 Scope of study

This study focused on the development of fibre interferometer for multi-parameter sensing using DCF. The development process starts with conceptual sensor design, followed by sensor fabrication, and finally, sensor experimentation. The main strength of this research lies in the substantial series of fabrication and experimental works. All of the sensor designs employed different fabrication procedure and unique setup for performance evaluation. Each of the distinctive scope of this study is further described in the following.

1.4.1 Conceptual Sensor Design

First, the sensor design was produced from the preliminary understanding of light behaviour. The sensor structures in drawing form were analysed by using BeamProp software. BeamProp analysis gives several important results, including optical field distribution and sensor spectrum. Field distribution result provides certainty on the functionality aspect in terms of wave splitting and combining. Although the software is capable to perform spectra and sensitivity analyses, this analysis is limited within field distribution analysis only because of time constraint. Related sensing models for specific sensors were developed to determine the sensor responses qualitatively. The conceptual sensor design and numerical simulation are detailed in Sections 3.3 and 3.4, respectively.

1.4.2 Sensor Fabrication

The conceptual sensors were realised into actual device through fabrication process carried out using in-house facilities. Systematic fabrication procedures were developed for each sensor design to improve the quality and repeatability of manufactured sensors. Sensor fabrication process is elaborated in **Section 3.5**.

1.4.3 Sensor Experimentation

Sensor experimentation was executed to quantify the actual sensing performance of each proposed design. Sensor experimentation mainly involved the preparation of testbeds and the characterisation process. Each design may require different testbeds due to different detected measurands. Meanwhile, the characterisation process is related to the procedures of collecting data from the sensor. Experimentation works were carried out in controlled environment. For practical application, further test may be required in order to validate the repeatability and robustness in uncontrolled environment. Sensor experimentation is described in detail in **Section 3.6**.

1.5 Significant of Study

Overall, the main contributions of this research work are based on the development of three novel sensor designs described in the previous chapters.

(a) Development of a novel MI based on DCF for temperature and RI sensing. The details are described in the following:

i. Development of a sensing concept, whereby detection of RI relies on Fresnel’s reflection at the tip of DCF (hence change of optical power), while detection of temperature relies on the thermo-optic property of optical fibre (hence change of wavelength and power). By selecting a particular reference point, both RI and temperature responses can be differentiated.
ii. Development of a related sensing model for the sensor as presented in **Section 3.3.1.**
iii. Verification of sensor functionality for temperature and RI sensing through experimental work.

(b) Development of a novel MZI based on ESMF and DCF for RI and discrete liquid level sensing. The details are described in the following:

i. Development of a novel sensing concept that combines both requirements of RI sensor and liquid level sensor. Two ESMF sections serve as the two discrete sensing points sensitive to the surrounding material. The DCF is not sensitive to the surrounding material and it is part of the interferometer arm. The sensor provides distinctive responses to different RIs and liquid levels.

ii. Development of a related sensing model for liquid level sensor as presented in Section 3.3.2.

iii. Development a systematic fabrication procedure that involved:
   - Etching process to obtain consistent fibre thickness
   - Splicing between ESMF and DCF/MMF, i.e., between thin fibre and normal fibre

iv. Verification of sensor functionality for RI and liquid level sensing demonstrated from single- and dual-point measurements.

(c) Development of a novel MZI based on DCF for small curvature (or displacement) and large curvature (or circumference) sensing. The structure demonstrates the highest curvature measurement range when compared to all the other existing sensors.

1.6 Thesis Overview

First and foremost, Chapter 1 presents brief introduction of optical fibre sensor to provide overview description of the research topic to readers. It is followed by research motivation and problem statement which emphasize on the contemporary issues concerned by this research work. Based on the problem statement, the research objectives were formulated. Chapter 1 also covers the scope of study and summary of contributions of the research work. Chapter 2 presents the literature review related to this research work. Initially, the review is focused on general topics, such as the types of optical fibre, the concept of fibre interferometer, and the construction method of in-line fibre interferometer. Next, the review focuses on sensor designs. The literature review is composed of three parts based on the three sensor designs proposed in this study, namely for (i) temperature and RI sensing, (ii) RI and discrete liquid level sensing, as well as (iii) displacement and curvature sensing. The research gap, novelty, and contribution of the proposed designs are clearly identified through comprehensive and critical review. Chapter 3 describes the methodology implemented for the main research components, including conceptual design and theoretical model, numerical simulation, fabrication, experiment setup, and experiment procedure. Chapter 4 reports the experiment results for all sensor designs. Section 4.2 presents the novel Michelson interferometer (MI) sensor based on DCF for temperature and RI sensing. In this design, two sensing mechanisms were utilised; first, detection of temperature based on the thermo-optic effect of fibre, and second, RI based on Fresnel's reflection at the fibre tip. The sensor should detect temperature change through wavelength shift of the sensor reflection spectra, while RI shift from the power shift of the reflection spectra. Section 4.3 reports the novel Mach-Zehnder interferometer (MZI) with dual compact sensing points for RI and discrete liquid level sensing. In this novel design, two sections of etched single mode fibre (ESMF) were utilised as the discrete sensing points to enable RI and liquid level sensing. Section 4.4 reports a novel MZI based on DCF for a wide range of curvature sensing. The sensor should operate within the smallest radius possible (the largest possible curvature) before the breaking point of the fibre. Lastly, Chapter 5 presents the conclusion, and future endeavours, of this research topic.

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LIST OF PUBLICATIONS

Journal Papers

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