DROPLET BENT MULTIMODE FIBER SENSOR FOR TEMPERATURE AND REFRACTIVE INDEX MEASUREMENT

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DEDICATION

This thesis is dedicated to my father, who taught me that the best kind of knowledge to have is that which is learned for its own sake. It is also dedicated to my mother, who taught me that even the largest task can be accomplished if it is done one step at a time.

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ABSTRACT

This thesis presents an original research work on bent multimode fiber sensor for refractive index (RI) and temperature sensing. The fiber sensor structure is formed by a successive splicing between single mode-multimode-single mode (SMS) fibers. A droplet bent shape is introduced in the multimode fiber section for excitation of modes into the acrylate coating. The excitation of higher-order modes into the acrylate coating is particularly interesting due to high thermo-optic coefficient (TOC) of acrylate which could improve temperature sensitivity. While evanescent field interaction of modes at the acrylate surface with surrounding material could be used for RI and temperature sensing. These modes experienced phase changes due to surrounding temperature and refractive index changes, consequently shifting the spectra of the sensor. This study covers numerical simulation using BeamPROP, sensor fabrication and experimental work. The sensor structure was simulated using BeamPROP software to understand light distribution and mode distribution inside the bent multimode fiber from the field pattern such that the bent structure is suitable for sensing. Different bending radiuses of 3.5 mm, 5 mm, and 7.5 mm were fabricated and tested. The highest refractive index sensitivity was obtained from 3.5 mm bent sensor with sensitivity of 42.41 nm/refractive index unit (RIU) tested between 1.30-1.395 RIU. Meanwhile, highest temperature sensitivity of 1.317 nm/°C was attained using 5 mm bent sensor between 25 °C to 35 °C. The low cost and simple sensor fiber structure is desirable in many applications including liquid food industry, and water quality monitoring system.

ABSTRAK

Tesis ini membentangkan karya penyelidikan asal pada sensor gentian mod pelbagai yang lengkung untuk indeks biasan (RI) dan penderiaan suhu. Struktur sensor gentian dibentuk oleh penyambungan berturut-turut antara mod tunggal- mod pelbagai -mod tunggal (SMS). Lengkung berbentuk titisan diperkenalkan di bahagian gentian mod pelbagai untuk pengujaan mod ke salutan akrilat. Pengujaan mod aras tinggi ke salutan akrilat sangat menarik kerana nilai pekali termosal optik (TOC) akrilat yang tinggi dapat meningkatkan kepekaan suhu. Sementara interaksi medan evanescent di permukaan akrilat dengan bahan sekitar dapat digunakan untuk pengesanan RI dan suhu. Mod ini mengalami perubahan fasa disebabkan suhu sekitar dan perubahan indeks bias, seterusnya menganjakkan spektrum sensor. Kajian ini merangkumi simulasi berangka menggunakan BeamPROP, fabrikasi sensor dan kerja eksperimen. Struktur sensor disimulasikan menggunakan perisian BeamPROP untuk memahami pengedaran cahaya dan pengedaran mod di dalam gentian mod pelbagai yang lengkung dari corak medan sehingga struktur lengkung bersesuaian untuk penginderaan. Jejari lenturan yang berbeza iaitu 3.5 mm, 5 mm dan 7.5 mm telah difabrikasi dan diuji. Kepekaan indeks biasan tertinggi diperolehi daripada sensor lengkung 3.5 mm dengan kepekaan unit indeks 42.41 nm / induktif (RIU) diuji antara 1.30-1.395 RIU. Sementara itu, kepekaan suhu tertinggi 1.317 nm / ˚C dicapai menggunakan sensor lengkung 5 mm antara 25 ° C hingga 35 ° C. Struktur gentian sensor kos rendah dan mudah adalah dikehendaki dalam kebanyakkan aplikasi termasuk industri makanan cecair dan sistem pemantauan kualiti air.

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LIST OF ABBREVIATIONS

EMI	-	Electromagnetic Interference
FOS	-	Fiber Optic Sensor
FBC	-	Fiber Bragg Grating
MMI	-	Multimode Interference
MMF	-	Multimode Fiber
SMF	-	Single- mode Fiber
SMS	-	Single-mode-Multimode-Single-mode
TIR	-	Total Internal Reflection
LANs	-	Local Area Networks
RIU	-	Refractive Index Unit
STMS	-	Single-mode- Tapered multimode- Single-mode
SP	-	Side-polishing
TOC	-	Thermo-optic coefficient
OSA	-	Optical spectrum analyzer
TE	-	Transverse electric
TH	-	Transverse magnetic
TEM	-	Transverse electric and magnetic
TEC	-	Thermal-expansion coefficient

LIST OF SYMBOLS

$E(r, 0)$	-	Field distribution
C_m	-	Coupling efficiency
$F_{m(1)}$	-	Field profile of zero mode order
LP_{0m}	-	MMF eigenmodes
M	-	Eigenmodes MMF number
a	-	Radius of MMF
n_{cl}	-	Refractive index of MMF cladding
n_{co}	-	Refractive index of MMF core
λ	-	Wavelength
Z	-	Propagation distance
B_m	-	Propagation constant
λ_0	-	Operating wavelength/cut off wavelength
n	-	Refractive index
c_o	-	Speed of light in vacuum
c_i	-	Speed of light in medium
I	-	Angle of incidence
R	-	Angle of refraction
NA	-	Numerical aperture
π	-	Pi
P_{11} *and* P_{12}	-	Component of the photo-elastic tensor
V	-	Poisson's ratio
R_{eff}	-	Effective bent radius
I	-	Intensity
Δn_{eff}	-	Effective index difference between core and coating
$\emptyset_0$	-	Initial phase difference of the interference
T	-	Temperature
dn/dt	-	Thermos optic coefficient of fiber material

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CHAPTER 1

INTRODUCTION

1.1 Research Background Study

Fiber Optic Sensor (FOS) technology has experienced a tremendously growth recently due to their unique characteristics over the conventional electronic sensors such as lightweight, immunity to electromagnetic interference (EMI), high sensitivity, easy fabrication and cost-effective [1]. There are several types of FOS that are available currently including fiber Bragg grating (FBG), fiber laser, fiber interferometer and fiber multimode interference (MMI) sensors [2].

Nowadays, fiber optic sensor based on multimode interference (MMI) effect has become one of the promising technologies in niche sensing applications. MMI only occurs in multimode fiber when the modes that are supported by the multimode fiber (MMF) are excited and interfering with each other as it propagates along the MMF.

Implementation of MMI effect based on single mode-multimode-single mode (SMS) provides attractive characteristics such as simple preparation, high sensitivity and good spectral characteristics. This topic has been actively researched in the detection of different parameters including temperature, refractive index and vibration measurements. There are several methods that have been introduced in order to improve the SMS fiber sensor sensitivity such as chemical etching [3-5], tapering [6-9], side-polishing [10-11], liquid core MMF [12], polymer cladding [13], and bending [14-18] which demonstrated certain response to particular measurements. This thesis performs systematic study on SMS structure in order to obtain clear understanding of its operation.

1.2 Problem Statement

The main sensor criterion emphasized for this research work is fabrication simplicity which means sensor can be fabricated using basic optical laboratory equipment with straightforward fabrication process. Performance such as sensitivity and sensor size are also important and may be varied depending on implementation of the technique. Before proceeding to the next discussion, it is convenient to stress that most of the available techniques including tapering, etching, side -polishing, polymer cladding, and liquid core MMF require relatively complex or lengthy fabrication process over the chosen bending technique. Thus, the following discussion only focuses on the fabrication process while details on the performance will be discussed in Chapter 3.

Etching technique requires the use of hydrofluoric acid which is dangerous to handle and consistently need to be replaced [19]. On the other hand, design that is based on tapering process may require the use of specialized fabrication equipment with ultra-precise alignment [20]. The highly precise equipment may suggest high cost to purchase and maintain the fabrication equipment. For side-polishing, there are several techniques available including side polishing such as v-groove polishing, D-shaped polishing and wheel polishing [21]. All three side-polishing require multiple fabrication stages. One main issue of the polishing techniques is that the difficulty to achieve cost-effective way to control the polishing depth in order to achieve high measurement sensitivity [10]. The v-groove polishing technique causes permanent fiber deformation [21]. It is less suitable for practical point of view. Meanwhile, liquid core MMF design involves complex process to fill in hollow fiber with suitable high thermo- optic coefficient (TOC) liquid and specifically designed for temperature sensing only.

Lastly, the polymer coated MMF design involves time-consuming fabrication process where the cladding of the MMF need to remove through etching process and replaced with polymer of high TOC. Compare to other techniques, bending technique requires the simplest in fabrication process and at the same time may produce satisfactory performance [14]. Therefore, bending technique has been chosen as sensitivity enhancement technique for MMI sensor. Even though, the bent MMI fiber sensor has been reported previously [14-18], it is found that the presented works are lacked of study on the effect of the proposed structure to the sensor sensitivity, less thoroughly studied on the sensor potential to be used in other application such as refractive index measurement, and unclear understanding on proposed structure operation in sensor measurement.

1.3 Research Objectives

Based on the problem statement, the research objectives of this work are set as the followings:

(a) To perform numerical analysis on bent SMS structures in order to understand the effect of bending to light field distribution and mode distribution using BeamPROP.

(b) To fabricate the bent droplet bent MMF fiber sensor for temperature and refractive index sensing.

(c) To test and verify the proposed system

1.4 Scope of Work

In order to achieve the research objectives, the following works were carried out:

1.4.1 Numerical Simulation

The bent SMS structure was identified to be used as the sensing platform due to its simplicity. Simulation work was carried out using BeamPROP software that uses finite difference Beam Propagation Method. The analysis focused on light field and mode distribution inside the SMS fiber structure when specific bending is applied. The presences of leaky modes need to be confirmed through simulation as it was used as the sensing mechanism of the structure.

1.4.2 Experiment and Data Analysis

Experimental works comprises of sensor fabrication, equipment setup and sensor testing. The MMI fiber sensor was fabricated by using in-house facilities. The sensor head of the MMI fiber sensor was formed by permanent bent of an MMF section. Then, the MMI fiber sensors were tested with series of Cargile AAA oil that have six different refractive index values of 1.30, 1.32, 1.34, 1.36, 1.38, and 1.395 RIU. The refractive index values were picked with the increment of 0.02 starts from 1.30 RIU; therefore, it is choosing up to 1.395 RIU. The refractive index of Cargile AAA oil that are available is up to 1.395 RIU, therefore the refractive index that are choose is up to 1.395 instead of 1.40 RIU. For the temperature measurement, the experiment was conducted at room temperature of 25 °C up to 35 °C with 1 °C increment. Finally, the sensor sensitivity was determined based on the wavelength shift of the output spectra. MATLAB software was used in the data analysis.

1.5 Significance of Work

It is important that sensor can be produced in bulk quantity in simple and economical way which is demanded by industries nowadays. Thus, bending approach is chosen in this study due to its simplicity and relatively good sensitivity to the targeted parameters. The contributions of this study are summarized as follows:

1) This study will contribute to the deep understanding on the effect of bending to the MMI fiber sensor performances.
2) This study helps sensing industry to explore in greater detail on how to improve the sensing performance using bending techniques.

3) This study provides a greater understanding on the properties of light distribution and mode distribution inside the SMS fiber structure.

4) This study will provide the understanding on the effect of polymer coating to the sensor sensitivity.

1.6 Thesis Outline

Chapter 1 presents the research background of the study, problem statements, and objectives, scope of work and general outline of this thesis. Chapter 2 presents literature review on related topics which eventually focusing onto sensitivity enhancement technique in SMS structure. Chapter 3 presents the research methodology that explains procedures implemented in this study. Chapter 3 also describes simulation that was carried out using BeamPROP software to investigate the light and mode distribution inside the fiber sensor head. Subsequently, this chapter provides explanation on the fabrication of the fiber sensor design which involved splicing and bending process. Besides that, the experimental step is also discussed for both refractive index and temperature measurements. Chapter 4 presents the outcome of simulation and the experiment works. Finally, conclusions and future works are presented in Chapter 5.

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