UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Faculty of Electronics and Computer Engineering

SENSITIVITY ENHANCEMENT OF OPTICAL FIBER SENSOR FOR LIQUID SENSING APPLICATIONS BY USING MACH-ZEHNDER INTERFEROMETER

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NUR HIDAYAH BINTI SULAIMAN

A thesis submitted
in fulfillment of the requirements for the degree of Master of Science in Electronic Engineering

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DECLARATION

I declare that this thesis entitled "Sensitivity Enhancement of Optical Fiber Sensor for Liquid Sensing Applications by Using Mach-Zehnder Interferometer" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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APPROVAL

I hereby declare that I have read this thesis and my opinion this thesis is sufficient in term of scope and quality for the award of Master of Science of Electronic Engineering.

Signature	:	…………………………………………
Supervisor Name	:	DR. HANIM BINTI ABDUL RAZAK
Date	:	…………………………………………

DEDICATION

بسم الله الرحمن الرحيم

To Mama, Ayah and my soulmate.

To my sister, brothers and friends.

You all are my strongest bone

ABSTRACT

Liquid sensing application plays an important role in biological, chemical and food industries. A conventional electrical based sensor is exposed to electromagnetic interference (EMI) which generates the electrical sparks. Hence, the fiber optic sensor (FOS) has attracted a great interest in sensing applications due to the immunity to EMI, high sensitivity and compact size. Interferometer is commonly used in the development of the FOS in liquid measuring system. In this research project, the FOS has been employed for liquid sensing application by using a Mach–Zehnder Interferometer (MZI). There are two main MZI structures that involved in this research, which are Singlemode-Multimode-Singlemode (SMS) and Multimode-Singlemode-Multimode (MSM) structure that provides low cost of fabrication. The device was developed by using simple and less complex fabrication which is fusion arc splicing technique for splicing the three main sections of FOS. The sensitivity analysis was tested on different liquid concentration such as water, 1.0 mol sucrose and oil with the refractive index of 1.333 RIU, 1.384 RIU and 1.464 RIU respectively. This research manipulated the sensing-region section to analyze the response of FOS towards different liquid concentration. Firstly, the length of the sensing region was varied to 4 cm, 8 cm and 12 cm prior to sensitivity enhancement method. The resultant of resonance wavelength shifting generates different sensitivity and the length of the sensor area which demonstrated the highest sensitivity was selected for the next sensitivity enhancement process. The sensitivity enhancement process for this research is based on the chemical etching and macrobending effect that aimed to generate more evanescence field at the sensing region. According to the etching process analysis, time taken for each sensing-region to reach 55 µm diameter was 16 minutes for SMS structure and 23 minutes for MSM structure. Meanwhile for the macrobending effect, the sensing-region with a bending diameter of 2.8 cm, 3.3 cm and 4.0 cm were analyzed. The results of the FOS with and without the sensitivity enhancement were observed. This research demonstrated improvement sensitivity by 1663.31% for SMS structure and 827.08% for MSM structure.

ABSTRAK

Penderia cecair merupakan aplikasi yang sangat penting dalam sistem pengukuran cecair terutamanya terhadap industri biologikal, kimia dan pemakanan. Penderia cecair konvensional yang berasaskan elektrikal terdedah kepada gangguan elektromagnetik yang berupaya mewujudkan percikan elektrik. Maka dengan itu, penderia gentian optik telah mendapat perhatian yang sangat meluas dalam aplikasi penderiaan. Hal ini kerana, penderia gentian optik terpelihara daripada gangguan elektromagnetik, kepekaan yang tinggi, malah hadir dalam saiz yang sangat padat. Interferometer kerap digunakan dalam sistem pengukuran cecair. Interferometer Mach-Zehnder (MZI) telah digunakan dalam projek ini untuk aplikasi penderia cecair. Terdapat dua jenis struktur MZI yang digunakan dalam projek ini yang rendah kosnya iaitu mod tunggal-mod pelbagai-mod tunggal (SMS) and mod pelbagai-mod tungggal-mod pelbagai (MSM). Selain itu, fabrikasi peranti cecair penderia ini juga menggunakan teknik fabrikasi yang lebih mudah dan tidak kompleks iaitu penyambungan lengkungan untuk menyambungkan ketiga-tiga bahagian utama struktur peranti. Projek ini menggunakan tiga jenis cecair yang mempunyai kepekatan yang berbeza untuk menganalisa kepekatan penderiaan. Jenis-jenis cecair yang dianalisa ialah air, sukrosa 1 mol dan minyak, masing-masing mempunyai indeks biasan 1.333 RIU, 1.384 RIU dan 1.464 RIU. Analisa projek ini telah dilakukan berdasarkan tindak balas penderia cecair terhadap cecair yang mempuyai kepekatan yang berbeza-beza dengan memanipulasikan bahagian penderia. Pada awalnya, kepanjangan bahagian penderia telah dimanipulasikan dengan 4 sm, 8 sm dan 12 sm. Peralihan panjang gelombang resonan telah menghasilkan kepekaan yang berbeza mengikut kepanjangan bahagian penderia. Panjang penderia yang mempamerkan kepekaan yang paling tinggi dipilih untuk proses peningkatan penderiaan yang seterusnya. Proses peningkatan kepekaan bagi projek ini adalah yang berdasarkan proses punaran kimia dan teknik lenturan makro. Teknik-teknik peningkatan kepekaan ini bertujuan untuk menghasilkan medan evanesen yang lebih tinggi di bahagian penderia. Analisa terhadap proses punaran kimia telah menunjukkan masa yang diambil untuk mengecilkan saiz garisan pusat kepada 55 µm adalah 16 minit untuk struktur SMS dan 23 minit bagi struktur MSM. Manakala untuk kesan lenturan makro, bahagian penderia akan dilenturkan lengkungan dengan garisan pusatnya berukuran 2.8 sm, 3.3 sm dan 4.0 sm. Kajian ini memerhatikan tindak balas peranti penderia gentian optik sebelum dan selepas teknik peningkatan penderiaan. Projek ini telah berjaya meningkatkan prestasi penderia gentian optik dengan struktur SMS sebanyak 1663.31% manakala struktur MSM sebanyak 827.08%.

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LIST OF ABBREVIATIONS

CW	-	Counter Clockwise
CCW	-	Counter Clockwise
EMI		Electromagnetic Interference
FBG	-	Fiber Bragg Grating
FPI	-	Fabry Perot Interferometer
FOS	-	Fiber Optic Sensor
FSR	-	Free Spectral Range
HBF	-	High Birefringent Fibers
HF	-	Hydrofluoric Acid
LP	-	Linearly Polarized
MI	-	Michelson Interferometer
MMF	-	Multimode Fiber
MSM	-	Multimode-Singlemode-Multimode
MZI	-	Mach-Zehnder Interferometer
NDS	-	Non-Dispersive Sensing
OPD	-	Optical Path Different
OTDR	-	Optical Time Domain Reflectometry
PCF	-	Photonics Crystal Fiber
PMF	-	Polarization Maintaining Fiber

POF	-	Plastic Optical Fiber
SD	-	Standard Deviation
SI	-	Sagnac Interferometer
SMF	-	Single mode Fiber
SMS	-	Singlemode-Multimode-Singlemode
RI	-	Refractive Index
RIU	-	Refractive Index Unit
TIR	-	Total Internal Reflection
TLS	-	Tuneable Laser Spectroscopy

LIST OF SYMBOLS

a	-	Acceptance angle
a_m	-	Field excitation coefficient
β_m	-	Propagation constant
c	-	Speed of light in the vacuum
x	-	Value for each data set
$\bar{x}$	-	Means of data set
E_0	-	Magnitude electrical field
$E\ (r)$	-	Electrical field
$E_m(r)$	-	Normalized modal electrical field
$E_m(x)$	-	Electrical field from the distance of x
n	-	Refractive index of the medium
n_{co}^{eff}	-	Effective refractive index of core
n_{clad}^{eff}	-	Effective refractive index of cladding
v	-	Speed of light in the medium
λ	-	Resonance wavelength of the optical signal
I	-	Intensity of optical signal
dp	-	Penetration depth
Lp	-	Linear polarization
L_m	-	Length of the sensing-region

M	-	Molarity
N	-	Number of modes
NA	-	Numerical aperture
P_{Loss}	-	Optical power loss
Rc	-	Critical radius
SD	-	Standard deviation
V	-	Normalized frequency parameter of a fiber
Vol	-	Volume of the solution
θ_c	-	Critical angle
Φ_θ	-	Angle incident ray of reflected to the normal line
Φ_{MZI}	-	Optical phase different
Δn_{eff}	-	Effective refractive index of core and cladding
$\Delta\lambda$	-	Wavelength separation in between to free spectral range
$\sum$	-	Sum off

LIST OF PUBLICATIONS

Hanim, A.R., Hidayah, N.S., Hazura, H., Idris, S.K., Mohd Zain, A.S., Salehuddin, F., and Maheran, A.A.H., 2017. A fiber optic sensor based on Mach-Zehnder interferometer structure for food composition detection. Microwave and Optical Technology Letters 60(4), pp 920-924).

Hidayah, N.S., Hanim, A.R., Hazura, H., Idris, S.K., Mohd Zain, A.S., Salehuddin, F., and Maheran, A.A.H., 2017. Modal Interferometer Structures and Splicing Techniques of Fiber Optic Sensor. Journal of Telecommunication, Electronic and Computer Engineering, 10 (2-2), pp.17–19.

Hidayah, N.S., Hanim, A.R., Hazura, H., Idris, S.K., Mohd Zain, A.S., Salehuddin, F., and Maheran, A.A.H., 2017b. Performance of different Mach-Zehnder interferometer (MZI) structures for optical modulator. Journal of Telecommunication, Electronic and Computer Engineering, 9 (2–8), pp.25–29.

CHAPTER 1

INTRODUCTION

1.1 Summary background

Over the past two decades the growth of products revolutions for optoelectronics and fiber optic communications has vigorously changed. The optoelectronics field contributes to the biological, chemical and food industries in terms of industry with a variance application such as compact disc players, laser printers, bar code scanners, and laser pointers. Meanwhile, the fiber optic communications industry also revolutionized the telecommunications industry by providing higher performance, more reliable telecommunication links with ever decreasing bandwidth cost (Fidanboylu and Efendioglu, 2009).

In recent years, fiber optic sensors (FOS) have developed from the laboratory research and development stage to practical applications. This is due to their specialty on sensitivity, size and immunity to electromagnetic interference in the biological, chemical and environment industries compared to conventional electrical sensors (Shi et al., 2012; Xue et al., 2012; Wo et al., 2013; Zhu et al., 2015; Azad et al., 2017).

Interference phenomenon influences the revolution of FOS as it manipulated the interference phenomenon and provides a high precision measuring systems (Krohn et al., 2014a). Mach-Zehnder interferometer (MZI) is among the application of the interference phenomenon that very effective for refractive index sensing. Recently, several types of interference optical fiber sensors have been developed to measure the liquid concentration based on the changes of the refractive index (Wang et al., 2010; Guzmán-Sepúlveda et al., 2013; Jiao et al., 2013; Yu et al., 2016). Refractive index (RI) sensing plays an important role in various chemical, medical and biological liquid measurements. On top of that, the simplicity in signal recovery is the superior property of this structure (K. T. V. Grarttan, 1999).

Figure 1.1 shows the scope of study of this research project that used on MZI structures of interferometric intrinsic FOS categories for refractive index sensor. The structures of MZI used in this research project utilized the standard fiber such as single mode fiber (SMF) and multimode fiber (MMF). The structures of MZI FOS consist three parts which are the lead-in, sensing-region, and lead out sections. Other than that, this research project proposed core mode mismatch as the major splicing techniques to fabricate the MZI structures which are Singlemode-Multimode-Singlemode (SMS) and Multimode-Singlemode-Multimode (MSM).

Moreover, this research project also proposed the sensitivity enhancement method for both MZI structures. The sensitivity enhancement aimed to enhance the evanescence field at the sensing-region that can be obtained by the chemical etching process and macrobending effect in sequential. The performance was analyzed based on the sensitivity response towards the changing of the refractive index of the tested solutions.