DEVELOPMENT OF FIBER-BASED SINGLEMODE-MULTIMODE FIBER WITH MICRO CONVEX LENS DISPLACEMENT SENSOR

NUR IZZATI ISMAIL

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Engineering (Electrical)

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

MAY 2016

Specially dedicated to my beloved parents, Ismail Che May and Che Embun Ali, my siblings and friends for their continuous support, prayers, encouragement and also understanding during my master programmes.

ACKNOWLEDGEMENT

In the name of Allah SWT, Most Gracious and Most Merciful. First and foremost, all praise to Allah S.W.T. for His guidance, blessing and grace that give me health and strength to be able to complete this research work and finally come out with this thesis.

I wish to express my sincere appreciation to my supervisor, Dr. Nor Hafizah Ngajikin and co-supervisors, Dr Asrul Izam Azmi and Dr Nik Noordini Nik Abd. Malik for their moral support and invaluable guidance throughout this research work. I am indebted for their effort and enthusiasm in reading and commenting my thesis. Special acknowledgements are extended to technicians and researchers of Photonic Research Laboratory Universiti Teknologi Malaysia (UTM) especially Mr Ahmad Hassan for his assistance and support throughout my experimental works.

I would also like to take this opportunity to convey my deepest gratitude to my parents and friends for their moral support, understanding and always be by my side whenever I am facing difficulties in pursuing my research. I am always grateful for their patience and confidence that they have in me.

Not forgotten, for those whose has been involved and contributed directly or indirectly in completing my master project, my gratitude is for them. Without their continued support and interest, this project and thesis would not have been the same as presented here. Finally, the financial support from Kementerian Pelajaran Tinggi (KPT) MyBrain and MARA are kindly appreciated.

ABSTRACT

Various sensitive industrial applications require micro-displacement detection in order to realize a precise movement control. This micrometer displacement can be detected using a fiber-based displacement sensor that offers micro displacement detection and is immuned against electromagnetic radiation. This kind of sensor, however, has limitations on its sensing range and sensitivity. In order to comprehend the limitations, a new configuration of fiber-based displacement sensor with improved sensing range and sensitivity is designed and presented in this thesis. The developed displacement sensor works according to the Fabry-Perot Interferometry (FPI) principle. In general, the proposed displacement sensor consists of two parts; an optical semireflecting fiber mirror attached with micro-convex lens as a sensor head and a highly reflective coated gold mirror. These two components are arranged in parallel to form a Fabry-Perot cavity. In this work, the new sensor configuration is realized by fusion splicing a segment of 9/125 μm single mode fiber (SMF) to one end of 10 mm long section of 62.5/125 multimode fiber (MMF). The other end of the MMF is ultraviolet (UV) cured with a liquid composition of Norland Optical Adhesive 61 (NOA) that forms a micro-convex lens at the sensor head. Physical characterization of the fabricated SMF-MMF with NOA micro-convex lens (SMF-MMF-Lens) sensor shows that this sensor has a reflectivity of 6.8% with 210 μm focal length, $f(h)$. These outcomes attribute to an increase of reflected optical power and also an improvement on the sensing range. In order to sense the displacement, 200 nm thickness of sputtered gold mirror is attached to the movable object for characterization process. The SMF-MMF-Lens sensor performances are analyzed in terms of intensity and fringe response analysis. For this purpose, a broad light source ranging from 1530 nm to 1565 nm wavelength is injected into the sensor and the reflected light is captured using an optical spectrum analyzer (OSA). The intensity response showed that this SMF-MMF-Lens sensor managed to sense displacement within 10 μm to 520 μm sensing range with sensitivity of 566.4 μW/μm. Employing OSA with 1 nm resolution results in the SMF-MMF-Lens sensor having resolution of about 1.77 pm/W. Within the tested range, 10 μm to 310 μm displacement range exhibits a good linear response which corresponds to 3/2 of the lens focal length. For the fringe response analysis, it is identified that the SMF-MMF-Lens sensor was able to detect displacement of 10 μm to 520 μm sensing range with the sensitivity of 0.0284 fringes/ μm. The entire sensing range for fringe analysis is linear. For comparison purposes, conventional sensors with SMF and SMF-MMF configurations are fabricated for sensor performance analysis. The sensitivity of SMF-MMF-Lens sensor improved at about 77.72% and 9.7% in comparison to the conventional SMF-MMF sensor for its intensity and fringes response analysis, respectively.

ABSTRAK

Pelbagai aplikasi industri yang sensitif memerlukan pengesanan anjakan mikro bagi merealisasikan pergerakan kawalan yang tepat. Anjakan mikro ini boleh dikesan menggunakan pengesan anjakan dasar gentian optik yang menyediakan pengesanan anjakan mikro dan kebal terhadap radiasi elektromagnet. Pengesan jenis ini, bagaimanapun, ada had pada julat pengesanan dan sensitivitinya. Bagi mengatasi had itu, satu konfigurasi baru pengesan anjakan jenis gentian optik dengan penambahbaikan julat pengesanan dan sensitiviti direka bentuk dan dikemukakan dalam tesis ini. Pengesan anjakan yang dicipta ini berfungsi berdasarkan prinsip Interferometer Fabry-Perot (FPI). Umumnya, pengesan anjakan yang dicadangkan mengandungi dua bahagian, di mana satu bahagian adalah cermin semi-pantulan gentian optik dan lensa mikro cembung sebagai kepala pengesan manakala satu lagi bahagian adalah cermin pantulan tinggi bersalut emas. Dalam kajian ini, konfigurasi pengesan anjakan baru direalisasikan dengan sambat lakuran satu bahagian 9/125 µm gentian mod tunggal (SMF) kepada satu hujung 10 mm panjang 62.5/125 µm gentian multimod (MMF). Satu lagi hujung MMF dirawat oleh sinar ultra ungu (UV) dengan satu komposisi cecair pelekat optikal Norland 61 (NOA) yang membentuk satu lensa mikro cembung di kepala pengesan. Pencirian fizikal pengesan SMF-MMF dengan lensa mikro cembung NOA (SMF-MMF-Lensa) yang telah dibentuk menunjukkan yang pengesan ini mempunyai 6.8% pemantulan dengan 210 µm jarak fokus, *f(h)*. Hasil ini menyumbang kepada pertambahan kuasa cahaya terpantul dan juga penambahbaikan kepada julat pengesanan. Bagi mengesan anjakan, 200 nm tebal cermin bersalut emas dilekatkan kepada objek bergerak untuk proses pencirian. Persembahan pengesan SMF-MMF-Lensa dianalisis dalam terma keamatan dan juga tindak balas pinggir. Untuk tujuan ini, sumber cahaya lebar berjulat dari 1530 nm ke 1565 nm jarak gelombang disuntik ke dalam pengesan dan cahaya pantulan dikesan menggunakan satu penganalisa spektrum optik (OSA). Tindak balas keamatan menunjukkan yang pengesan SMF-MMF-Lensa ini berjaya mengesan anjakan di antara 10 µm ke 520 µm julat pengesanan dengan sensitiviti 566.4 µW/µm. Menggunakan OSA dengan 1 nm resolusi menghasilkan pengesan SMF-MMF-Lensa dengan resolusi beranggaran 1.77 pm/W. Di antara julat pengesanan yang diuji, 10 µm ke 310 µm jarak anjakan mempamerkan tindak balas linear yang bagus, dimana ia sepadan kepada 3/2 jarak fokus lensa. Untuk analisis tindak balas pinggir, ia dikenal pasti bahawa pengesan SMF-MMF-Lensa mampu mengesan anjakan 10 µm ke 520 µm jarak kesan dengan sensitiviti 0.0284 pinggir/µm. Keseluruhan julat pengesanan bagi analisis pinggir adalah linear. Untuk perbandingan, pengesan konvensional dengan konfigurasi SMF dan SMF-MMF difabrikasi untuk analisis prestasi pengesan. Sensitiviti pengesan SMF-MMF-Lensa dapat dipertingkatkan dalam anggaran 77.72% dan 9.7% berbanding pengesan konvensional SMF-MMF bagi analisis tindak balas keamatan dan pinggir.

TABLE OF CONTENT

2 REVIEW OF FIBER DISPLACEMENT SENSOR 11

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

f_r - Fiber radius

D_{MMF} - Diameter of MMF core

L_{MMF} - MMF length

$L_{re-imaging}$ - Re-imaging distance

P_r - Reflected optical power

P_t - Injected optical power

R_1 - Radius of curvature of lens that closest to light source

R_2 - Radius of curvature of lens that farthest to light source

$R_{Au}.$ - Reflectivity of A_u mirror

U_{Au} - Uniformity of A_u mirror

$f_p(h)$ - Length from vertex of lens to focal point

k_{Au} - Extinction coefficient of gold

$n_{25°C}$ - Refractive index of NOA 61 at temperature 25 °C

n_{Au} - Refractive index of gold

n_{NOA} - Refractive index of NOA

$n_{cladding}$ - Refractive index of MMF cladding

n_{core} - Refractive index of MMF core

n_{lens} - Refractive index of lens

t_{Au} - Thickness of gold mirror coating

λ_0 - Free space wavelength

a - Core radius

$\boldsymbol{A}$ - Sensitivity in inverse third law function

A_u - Gold

b - Sensitivity in quadratic transfer function

$\boldsymbol{B}$ - Constant in inverse third law function
C - Concentric
c - Y-intercept of a transfer function
$\boldsymbol{C}$ - Constant and non-zero in inverse third law function
d - Length of FPI cavity
D - Displacement of gold mirror
D_0 - Initial displacement of mirror
$D_{\text{air holes}}$ - Diameter of air holes
$\boldsymbol{d_{COJ\text{-}MZI}}$ - Core-offset distance
D_{FCM} - Displacement by using FCM
$D_{\max}$ - Maximum displacement of mirror
F - Focal point
g - Length of SMF-silica
H - Hemicircular
h - Lens thickness
H_2O - Water
He-Ne - Helium-Neon
HF - Hydrogen fluoride
L - Length of cavity
$\boldsymbol{L_{COJ\text{-}MZI}}$ - Length of core-offset joint
m - Slope of a transfer function
n - Refractive index of FP cavity
N - Number of repeated pairs of alternative material
n_0 - Refractive index of originating medium
n_1 - Refractive index of the first alternating material
n_2 - Refractive index of the second alternating material
N_F - Number of fringes
NH_4F - Ammonium fluoride
n_s - Refractive index of terminating medium
P_{in} - Power of LS
P_{max} - Maximum reflected optical power
P_{min} - Minimum reflected optical power
P_{out} - Power measured by OSA

R	-	Random
r_1	-	Reflectivity of sensor head
r_2	-	Reflectivity of mirror
R^2	-	Coefficient of determination
R_a	-	Average roughness of surface
R_q	-	Root mean squared
R_s	-	Reflectivity of sensor
R_t	-	Distance between the highest and lowest points of surface
R_z	-	Average maximum of ten greatest peak-to-valley distances
$S_{SMF\text{-}MMF}$	-	Sensitivity of SMF-MMF Displacement Sensor
$S_{SMF\text{-}MMF\text{-}Lens}$	-	Sensitivity of SMF-MMF-Lens Displacement Sensor
T_{mn}	-	Percent of power transmitted from port *m* to *n* of a coupler
V	-	Volume of liquid lens
Λ	-	Pitch
y	-	Transfer function
α	-	Inclination angle
λ	-	Light center wavelength in FPI
λ_{FCM}	-	Center wavelength of source by using FCM
φ	-	Phase difference
$R(h)$	-	Micro radius of curvature
$f(h)$	-	Focal length of lens
p	-	Re-imaging point sequence number
r	-	Radius of lens

LIST OF ABBREVIATIONS

ASE	-	Amplified Spontaneous Emission
BBS	-	Broadband Source
COJ	-	Core-Offset Joint
EMI	-	Electromagnetic Interference
FCM	-	Fringe Counting Method
FDTD	-	Finite Difference Time Domain
FOS	-	Fiber Optic Sensor
FPI	-	Fabry-Perot Interferometer
HC-PCF	-	Hollow Core Photonic Crystal Fiber
IBS	-	Intensity-Based Sensor
IR	-	Infrared
LD	-	Laser Diode
LPG	-	Long Period Fiber Grating
LS	-	Laser Source
MATLAB	-	Matrix Laboratory
MFC	-	Microfiber Coupler
MI	-	Michelson Interferometer
MMF	-	Multimode Fiber
MMI	-	Multimode Interference
MZI	-	Mach-Zehnder Interferometer
NA	-	Numerical Aperture
NOA	-	Norland Optical Adhesive
OC	-	Optical Coupler
OPD	-	Optical Path Difference
OSA	-	Optical Spectrum Analyzer
PBS	-	Polarizing Beam Splitter

PC - Polarization Controller
PCF - Photonic Crystal Fiber
PIBS - Phase Interferometry-Based Sensor
PM - Power Meter
PMF - Polarization Maintaining Fiber
PMMA - Polymethyl Methacrylate Resin
POF - Polymer Optical Fiber
RF - Reciving Fiber
SCF - Suspended-Core Fiber
SI - Sagnac Interferometer
SLED - Superluminescent Light Emitting Diode
SMF - Single Mode Fiber
TF - Transmitting Fiber
UV - Ultraviolet

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background of Research

In line with the growth of interest in displacement monitoring system, it is increasingly important to provide displacement sensors with a good detection capability. For industries operating sensitive machines such as microscope, telescope, piping system, alarm system and keyboard instruments like pipe organs and accordions, displacement developed in the machines is a vital indicator of their conditions. This is because there is a certain tolerable displacement movement for the machines parts to experience before it is considered faulty. Early detection of faults in displacement movement could serve as a warning for the need of maintenance to prevent breakdown or serious damage. In fact, with the warning, overall operating cost can be considerably reduced since it prevents major damage on machines, minimizes disruption to production system, and eliminates the need for machines overhaul. Correspondingly, an effective measurement system for displacement detection is required in order to allow a precise movement control on the machines.

For the past few years, conventional displacement sensors working based on piezoelectric, magnetic, or capacitive principles are reported [1]–[4] Generally, these types of displacement sensors emerge as very popular due to cost-effective sensing elements. However, these sensors are limited in application since it is vulnerable to electromagnetic interference (EMI) [5],[6]. Fiber optic-based sensor is thus becoming an attractive choice for displacement measurement in the vicinity of EMI-based industries. The prominent features of fiber optic sensors (FOS) are their small size, lightweight, immunity to EMI and also high resistance in harsh environment [7]–[9]. In the last few decades, there have been numerous displacement sensors based on FOS technologies that were demonstrated.

The fiber optic displacement sensors are commonly categorized into intensity-based and phase interferometry-based sensor [10], [11]. As the name implies, the intensity-based sensors (IBS) concerns on the changes of light intensity while the phase interferometry-based sensor (PIBS) is on the phase changes. These intensity and phase parameters are dependent upon displacement changes. Hence, displacements movement in the machines can be induced from the variations in intensity or phase reading. The IBS and PIBS can be further classified into their respective techniques. In the IBS, two techniques are often used for measurements; non-contact IBS and micro bending IBS [12]. However, in displacement monitoring system, the non-contact IBS is more commonly used since it has a simpler system implementation. The micro-bending IBS is more suitable for strain and vibration measurements. As for the PIBS, they are frequently grouped into four, namely Mach-Zehnder, Sagnac, Michelson, and Fabry-Perot Interferometer (FPI) [13], [14]. Besides techniques, the FOS can also be defined by their operation mode, either transmission or reflection. In displacement monitoring system, a reflective type is more preferable since it offers better sensor performance [15], [16]. It is worth mentioning that the reflective displacement sensor performances are mainly attributed by two factors; configurations of sensor head and reflecting target [10], [17]. Since the sensor head employment involves a simpler process compared to the reflecting target in terms of simple fabrication, simple structure, small size, and low cost, hence the research on sensor head configurations is commenced for this thesis.

The sensor head research for reflective optical displacement sensor has been extensively investigated since there is a great demand for sensors that meet the required criteria. Various sensors based on IBS and PIBS have been demonstrated over the last few years [18], [19]. The reported sensors have their own pros and cons compared to their counterparts. For example, the IBS-based sensor is one of the simplest methods available for displacement measurement system. However, degradation of measurement accuracy over long periods, essential pre-calibration for reflecting target and complicated referencing arrangements present challenges for its practical applications in displacement monitoring [5]. On the other hand, sensors based on PIBS have received considerable attention due to its pertinent benefits as they are lower in cost, have simpler structures and eliminate the need for complex intensity referencing [13]. Among the available PIBS, the sensor incorporating FPI is more preferred since it requires neither a reference arm nor sophisticated stabilization unlike the other PIBS [5]. Many configurations of reflective displacement sensor based on the FPI technique are reported in the literature. These include sensor configurations of single mode fiber (SMF), single mode-multimode fiber (SMF-MMF) and single mode-photonic crystal fiber (SMF-PCF). However, the selections of the sensor configurations are highly motivated by two factors: simple fabrication and sensor performances (sensing range and sensitivity).

As such, the sensor performance in terms of sensing range and sensitivity are the two issues that inspired the area of interest in this research. These issues can be resolved by two features: one is employing multiple mode excitation effects in sensor which leads to sensitivity improvement; the other is by employing a micro convex lens at the sensor head facet for increasing sensing range.

1.2 A review on Sensor Configuration based on FPI Technique

Research on sensor head configurations have gain considerable attention because they are producible at a low cost, easy to implement with simple fabrication and are able to provide a good sensor performance. Correspondingly, a brief review on the previously reported sensor head configurations have been outlined here [20]–[22]. As stated before, in the evolvements of fiber-based displacement sensor, the approaches to achieve better sensor performance (high sensitivity and wide sensing range) are usually grouped into two, sensor head configurations and reflecting target. Since this research focuses on the sensor head, a review on the reported sensor head configurations are discussed in this section. Note that this review is the case where a planar mirror is used as the reflecting target.

The following literature review focuses on previously developed sensor structures that employed the FPI technique. A simple sensor that consists of SMF has been reported by Sathitanon and Pullteap [23]. In the developed sensor system, a technique called Fringe Counting Method (FCM) is used. This method uses a program written in Visual C++ for counting the number of interference fringe present in the output response. From the counted fringes, displacement information can be obtained. This method is somewhat complicated as it involved several steps in order to extract the displacement information. It is noted that the sensor operation requires the use of a lot of equipment to sense the displacement like a photodetector, digital oscilloscope and a computer for processing displacement information. Hence, the sensor system built is not preferable as it could be complex and problematic. Instead, the use of one equipment such as an optical spectrum analyzer (OSA) as the detector can be serve as the solution to a better sensor system. Nevertheless, with the FCM employed in this work, the sensor managed to detect displacement within 1.28 µm to 96.01 µm. In the other works of Pullteap and Seat, a relatively small improvement on sensing range from 0.7 µm to 140 µm was achieved, albeit with some modifications on the FCM [24].

An improvement was later made by Dash et.al [25], [26] to increase the sensing range. The improvement is made possible by splicing a small piece of photonic crystal fiber (PCF) to a section of SMF. The developed SMF-PCF sensor exhibits a sensitivity of 32 pm/nm and sensing range from 100 µm to 700 µm by employing a wavelength shift analysis technique using OSA [25]. By using this technique, measurement is based on the wavelength shift of peak/dip determined from the interference spectrum. It is stated that PCF with large mode area with the presence of another FP cavity give rise to a composed interference pattern, thus enhancing the sensor's resolution and so does the sensing range. Even though PCF is known with such ability, but the implementation can be quite cumbersome as it requires certain splicing method and it is more expensive. This may increase the cost of the sensor system.

Taking into account its cost-effectiveness, MMF is therefore a viable choice compared with PCF at the sensor head. On top of that, MMF is beneficial for improving sensitivity, which is mainly attributed by the larger mode field diameter of MMF that is capable in boosting the power of the interference mode [27]–[29]. A displacement sensor composed of successive splicing between SMF and MMF has been investigated by Mehta et. al [30] as the displacement sensor. It is observed that with SMF spliced to a section of MMF, the sensing range is limited depending on the reimaging image constructed inside MMF [9]. This reimaging image depends on the length of MMF used for the splicing. With 10 mm length of MMF spliced to SMF, the presented displacement sensor can sense up to 200 µm displacement and sensitivity of -257.36 µm/ µm by adopting the same wavelength shift analysis technique.

The summary on developed sensor head configurations and its performances are tabulated in Table 1.1. Undoubtedly, from the table, it shows that more research contributions on sensor head configurations are required for sensor performance improvement.

Table 1.1: Summary of developed sensor head configurations and its performances

Configurations of Sensor Head	Analysis Techniques	Sensitivity	Sensing Range	Ref.
SMF	Fringe Counting Method (FCM)	NM	1.28 µm to 96.01 µm	[23]
SMF	Modified Fringe Counting Method (FCM)	NM	0.7 µm to 140 µm	[24]
SMF-PCF	Wavelength Shift	32 pm/nm	100 µm to 700 µm	[25]
SMF-MMF	Wavelength Shift	-257.36 µm/ µm	Up to 200 µm	[30]

Notes: NM - Not Mentioned

1.3 Problem Statement

For the past few years, there are great demands for a good and tolerable sensor performance in displacement monitoring applications. However, there are a few issues to be resolved in order to achieve a good displacement sensor performance. Some of them are complexity of the system, sensor fabrication as well as the limitation in sensor performance (sensitivity and sensing range). As stated before, there are two distinct factors that affect the sensor performance: the sensor heads configurations and the reflecting target. However, instead of researching both factors, this study focuses on one that involves simpler implementation which is the sensor heads configurations.

Based on the summary of previous literature, it is found that studies on sensor head configurations commonly resulted in the limitation of sensitivity and sensing range. Therefore, in order to comprehend the limitation in the sensor's sensing range, an improvement on the SMF-MMF sensor was done with an addition of a micro convex lens. The use of micro convex lens results in the light emitting from the sensor head being focused onto the reflecting target, thus increasing the intensity of the reflected light [11]. Since the new sensor has a higher reflected light, it is therefore believed that the sensitivity of the sensor could be improved accordingly. For the analysis technique, the intensity response technique is used instead of the wavelength shift technique.

As stated before, the wavelength shift technique is a wavelength-dependent technique whereby for different positions of mirror that act as a reflecting target, different wavelength will correspond to the mirror displacement variation. Thus, this effect can be exploited to denote the displacement between the sensor head and the mirror. However, in this work, in order to investigate the relationship of intensity against the displacement of reflecting target, the intensity response technique is used instead of the wavelength shift response. This is because the sensor performance is predicted to improve if the reflected light intensity collected by the detector increases.

Besides intensity response, the fabricated sensor is also investigated in terms of fringe response analysis. This is because displacement is highly dependent on the length of FPI cavity. Any change in the length of cavity will result in a shift of FPI interference fringe pattern. As such, any displacement change can be determined from the measured fringe shift. Thus, by analysing the output in terms of fringes response, the displacement is expected to be detected with a high precision, which would result in high sensitivity and better linear range [10]. Therefore, as a conclusion, intensity and fringes response technique analyses on the new sensor are presented in this thesis.

1.4 Objective of Research

From the problem addressed in the previous section, the objective of this research can be specified as follows:

To design, fabricate and characterize a new configuration of displacement sensor head that improves sensitivity and sensing range with the use of simple fabrication techniques.

1.5 Scope of Research

In order to accomplish the objective of this work, the scopes of research is set as follows:

1. Comparative review of fiber-based displacement sensor based on its working principles, operation mode and fabrication method.
2. Modelling and simulation of micro convex lens in Optiwave Finite Difference Time Domain (OptiFDTD) software.
3. Evaluation of light propagation behaviour from numerical analysis of the micro convex lens.
4. Fabrication of the new sensor using two simple methods which are fusion splicing and ultraviolet (UV) curing.
5. Physical characterization of the fabricated sensor in terms of splicing loss, lens shape, height of lens, focal length, reflectivity and fringe visibility
6. Displacement characterization of the fabricated sensor in terms of sensitivity and linearity range for intensity response analysis

7. Displacement characterization of the fabricated sensor in terms of sensitivity for fringe response analysis.
8. Comparison of the fabricated sensor responses to the conventional SMF and SMF-MMF responses.

Note that the sensor development processes which comprises numerical simulation, fabrication and characterization is simple and cost-effective. From the analyses, this sensor is expected to improve sensitivity and sensing range.

1.6 Overview of Thesis

As discussed previously, this thesis is significantly devoted for the development of the new fiber-based displacement sensor. In order to briefly designate each development processes, the following thesis overview may assist the reader at a glance.

This thesis is organized into five chapters. Chapter 1 is an introduction to the project which covers research background, objective, problem statement and scope of work.

The rest of this thesis is constructed as follows. Chapter 2 reviews on the working principles, operation mode and fabrication methods of displacement sensor. Starting from the working principles, the displacement sensor is categorized into two types, namely IBS and PIBS. Following this, previous works on fiber-based displacement sensor are studied. Theory on the micro convex lens as well as its fabrication techniques are outlined in this chapter. A few of fabrication techniques are discussed based on fabrication complexity, implementation cost, practicality and also sensor feasibility. Displacement sensor analysis in terms of sensitivity and sensing range is also discussed in brief. The new displacement sensor configuration for this research work is proposed in the last part of Chapter 2.

Chapter 3 emphasizes on the numerical analysis, fabrication process, reflectivity and also physical characterization of the sensor. Along the way, various issues have been outlined. This includes the light propagation behaviour with presence of micro convex lens, fabrication techniques, reflectivity and lens focal length measurement.

Chapter 4 provides the displacement characterization of the fabricated sensor. As such, for the characterization, the sensor response is analysed in terms of intensity and fringes. Performance comparisons of the reported displacement sensor with the conventional sensors have been included in this thesis for properly distinguish the significant contributions of this work.

The last chapter, Chapter 5 remarks the conclusions and contributions of this thesis. Some suggestions for future research are also provided in that chapter.

REFERENCES

[1] F. Zhu, J. W. Spronck, and W. C. Heerens. A Simple Capacitive Displacement *Sensor. Sensors and Actuators A,* 1991. 27:265–269.

[2] R. Puers. Capacitive sensors: When and how to use them. *Sensors Actuators A Phys.*, 1993. Vol. 37–38: 93–105.

[3] C. Chiriac and H. Chiriac. Magnetic field and displacement sensor based on linear transformer with amorphous wire core. *Sensors Actuators A Phys.*, Sept 2003. 106(1–3): 172–173.

[4] T. K. Gangopadhyay and P. J. Henderson. Vibration: history and measurement with an extrinsic Fabry–Perot sensor with solid-state laser interferometry. *Appl. Opt.*, 1999. 38(12): 2471–2477.

[5] T. K. Gangopadhyay. Prospects for fibre Bragg gratings and Fabry-Perot interferometers in fibre-optic vibration sensing. *Sensors Actuators A Phys.*,2004. 113(1): 20–38.

[6] H. Chaurasiya. Recent Trends of Measurement and Development of Vibration Sensors. *Int. J. Comput. Sci. Issues*, 2012. 9(4).

[7] B. Mhdi, S. Ministry of, B. I. Technology, N. Aljaber, S. Aljwas, and A. Khalid. Design and construction of optical fiber sensor system for detection of stress and fine motion. *Int. J. Nano Devices, Sensors Syst.*, 2012. 1(1): 25–33.

[8] S. Pullteap. Development of a Fiber based Interferometric Sensor for Non-contact Displacement Measurement. *International conference on Computer, Electrical, and Systems Science, Paris (France)*, 2010. 1475–1479.

[9] J.-H. Chen, X.-G. Huang, J.-R. Zhao, J. Tao, W.-X. He, and S.-H. Liu. Fabry–Perot interference-based fiber-optic sensor for small displacement measurement. *Opt. Commun.*, 2010. 283(17): 3315–3319.

[10] H. Z. Yang, X. G. Qiao, D. Luo, K. S. Lim, W. Chong, and S. W. Harun. A review of recent developed and applications of plastic fiber optic displacement sensors. *Measurement*, 2014. 48: 333–345.

[11] Zheng and Albin. Self-referenced reflective intensity modulated fiber optic displacement sensor.*Optical Engineering*,1999. 38(2): 227-232.

[12] Yoany Rodríguez García, Jesús M. Corres, and Javier Goicoechea. Vibration Detection Using Optical Fiber Sensors. *Journal of Sensors*, vol. 2010, Article ID 936487, 12 pages, 2010. doi:10.1155/2010/936487

[13] B. H. Lee, Y. H. Kim, K. S. Park, J. B. Eom, M. J. Kim, B. S. Rho, and H. Y. Choi. Interferometric fiber optic sensors. *Sensors*, 2012. 12(3): 2467–2486.

[14] T. K. Gangopadhyay. Non-contact vibration measurement based on an extrinsic Fabry–Perot interferometer implemented using arrays of single-mode fibres. *Meas. Sci. Technol.*, 2004. 15(5): 911-917.

[15] M. A. Zawawi, S. O. Keffe, and E. Lewis. Intensity-modulated fiber optic sensor for health monitoring applications : a comparative review. *Sensor Review*,2013. 33 (1): 57-67.

[16] M. Yasin, S. W. Harun, H. a Abdul-Rashid, and H. Ahmad. The performance of a fiber optic displacement sensor for different types of probes and targets. *Laser Phys. Lett.*, 2008. 5(1): 55–58.

[17] S. W. Harun, H. Z. Yang, H. Arof, and H. Ahmad. Theoretical and experimental studies on coupler based fiber optic displacement sensor with concave mirror. *Optik.*, 2012. 123: 2105–2108.

[18] S. Binu, V. P. M. Pillai, and N. Chandrasekaran. Fibre optic displacement sensor for the measurement of amplitude and frequency of vibration. *Optics and Laser Technology*, 2007. 39: 1537–1543.

[19] C. Chang, P. Tung, L. Shyu, Y. Wang, and E. Manske. Fabry – Perot displacement interferometer for the measuring range up to 100 mm. *Measurement*, 2013. 46(10): 4094–4099.

[20] S. Pullteap. Development of a Fiber based Interferometric Sensor for Non-contact Displacement Measurement. *World Academy of Science, Engineering and Technology*, 2010. 42: 980–984.

[21] Q. Zhang, T. Zhu, Y. Hou, and K. S. Chiang. All-fiber vibration sensor based on a Fabry–Perot interferometer and a microstructure beam. *JOSA B*, 2013. 30(5): 1211–1215.

[22] H. Y. Choi, G. Mudhana, K. S. Park, U. Paek, and B. Ha. Cross-talk free and ultra-compact fiber optic sensor for simultaneous measurement of temperature and refractive index. *Optics Express*,2010. 18(1):141-149.

[23] N. Sathitanon, and S. Pullteap. A fiber optic interferometric sensor for dynamic measurement. *International Journal of Computer Science and Engineering*, 2008. 2: 63 -66.

[24] S. Pullteap and H. C. Seat. An Extrinsic Fiber Fabry-Perot Interferometer for Dynamic Displacement Measurement. *Photonic Sensors*, 2015. 5(1): 50–59.

[25] J. N. Dash, R. Jha, J. Villatoro, and S. Dass. Nano-displacement sensor based on photonic crystal fiber modal interferometer. *Optic Letters*, 2015. 40(4): 467–470.

[26] R. Jha, J. Dash, and S. Dass. Ultrasensitive Displacement Sensor Based on Photonic Crystal Fiber Modal Interferometer. *Adv. Photonics*, 2014.

[27] L. V. Nguyen, D. Hwang, S. Moon, D. S. Moon, and Y. Chung. High temperature fiber sensor with high sensitivity based on core diameter mismatch. *Opt. Express*, Jul 2008. 16(15): 11369-11375.

[28] S. Silva, O. Frazão, J. Viegas, L. a Ferreira, F. M. Araújo, F. X. Malcata, and J. L. Santos. Temperature and strain-independent curvature sensor based on a

singlemode/multimode fiber optic structure. *Meas. Sci. Technol.*, Aug. 2011. 22(8): 085201.

[29] Q. Wu, Y. Semenova, P. Wang, A. M. Hatta, and G. Farrell. Experimental demonstration of a simple displacement sensor based on a bent single-mode – multimode – single-mode fiber structure. *Meas. Sci. Technol.*, Jan. 2011. 22(8): 025203.

[30] A. Mehta, W. Mohammed, and E. G. Johnson. Multimode Interference-Based Fiber-Optic Displacement Sensor. *IEEE Photonics Technology Letters*, 2003. 15(8): 1129–1131.

[31] B. Lee. Review of the present status of optical fiber sensors. *Optical Fiber Technology*, 2003. 9: 57–79.

[32] J. E. Antonio-Lopez, P. LiKamWa, J. J. Sanchez-Mondragon, and D. a May-Arrioja. All-fiber multimode interference micro-displacement sensor. *Meas. Sci. Technol.*,2013. 24: 055104.

[33] D. Tosi, S. Poeggel, G. Leen, and E. Lewis. Adaptive filter-based interrogation of high-sensitivity fiber optic Fabry-Perot interferometry sensors. *Sensors Actuators A. Phys.*,2014. 206: 144–150.

[34] M.Jiang and E. Gerhard. Simple strain sensor using a thin film as a low-finesse fiber-optic Fabry-Perot interferometer. *Sensors Actuators A. Phys.*, 2001. 88: 41–46.

[35] P. Kishore, D. Dinakar, K. Srimannarayana, and P. V. Rao. Vibration sensor using 2× 2 fiber optic coupler. *Opt. Eng.*,2013. 52(10): 107104.

[36] P. M. Nieva, J. I. M. Kuo, and S. W. Chiang. A novel MOEMS pressure sensor : Modelling and experimental evaluation. *Sadhana*, 2009. 34(4): 615–623.

[37] T. Zhu, T. Ke, Y. Rao, and K. Seng. Fabry – Perot optical fi ber tip sensor for high temperature measurement. *OPTICS*, 2010. 283(19): 3683–3685.

[38] W. J. Pulliam, P. M. Russler, and R. S. Fielder. High-temperature high-bandwidth fiber optic MEMS pressure-sensor technology for turbine engine component testing. *Proc. SPIE*,2002. 4578: 229–238.

[39] V. K. Kulkarni, A. S. Lalasangi, I. I. Pattanashetti, and U. S. Raikar. Fiber optic micro-displacement sensor using coupler. *Journal of Optoelectronics and Advanced Materials*, 2006. 8(4): 1610–1612.

[40] G. Berkovic and E. Shafir. Optical methods for distance and displacement measurements Optical methods for distance and displacement measurements. *Advances in Optics and Photonics*,2012. 4: 441–471.

[41] H. Cao, Y. Chen, Z. Zhou, and G. Zhang. Theoretical and experimental study on the optical fiber bundle displacement sensors. *Sensors Actuators A Phys.*,May 2007. 136(2): 580–587.

[42] M. Yasin, H. a. Rahman, N. Bidin, S. W. Harun, and H. Ahmad. Fiber optic displacement sensor using fiber coupler probe and real objects. *Sens. Rev.*, 2012. 32(3): 212–216.

[43] C. Prelle, F. Lamarque, and P. Revel. Reflective optical sensor for long-range and high-resolution displacements. *Sensors Actuators A Phys.*, 2006. 127(1): 139–146.

[44] P. B. Buchade and a. D. Shaligram. Simulation and experimental studies of inclined two fiber displacement sensor. *Sensors Actuators A Phys.*, 2006. 128(2): 312–316.

[45] H. Golnabi. Fiber optic displacement sensor using a coated lens optic. *Rev. Sci. Instrum 71.*,2000. 71(11): 4314-4318.

[46] H. Z. Yang, K. S. Lim, S. W. Harun, K. Dimyati, and H. Ahmad. Enhanced bundle fiber displacement sensor based on concave mirror. *Sensors Actuators A Phys.*, 2010. 162(1): 8–12.

[47] T. Wang, S. Zheng, and Z. Yang. A high precision displacement sensor using a low-finesse fiber-optic Fabry-Pérot interferometer. *Sensors Actuators A Phys.*,1998. 69(2): 134–138.

[48] X. Zhou and Q. Yu. Wide-Range Displacement Sensor Based on Fiber-Optic Fabry-Perot Interferometer for Subnanometer Measurement. *IEEE Sens. J.*,2011. 11:1602–1606.

[49] H. C. Seat, P. Chawah, M. Cattoen, A. Sourice, G. Plantier, F. Boudin, J. Chéry, C. Brunet, P. Bernard, and M. Suleiman. Dual-modulation fiber Fabry-Perot interferometer with double reflection for slowly-varying displacements. *Opt. Lett.*, 2012. 37(14): 2886–2888.

[50] Y. Zhu and A. Wang. Miniature Fiber-Optic Pressure Sensor. *IEEE Photonics Technology Letters*,2005. 17(2): 447-449.

[51] J. Ma, H. Xuan, H. L. Ho, W. Jin, Y. Yang, and S. Fan. Fiber-Optic Fabry – Pérot Acoustic Sensor with Multilayer Graphene Diaphragm. *IEEE Photonics Technology Letters*, 2013. 25(10): 932–935.

[52] J. Li, X. Huang, G. Cheng, L. Chen, and X. Jin. Integration of a Micro Fabry - Perot Cavity and a Fiber Bragg Grating Sensor for Simultaneous Measurement of Stress and Temperature. *Microw. Opt. Technol. Lett.*, 2013. 55(10): 2440–2444, 2013.

[53] Miao Yu. *Fiber Optic Sensor Technology*. IMAC XXVI, University of Maryland, USA, Feb 2008.

[54] C. Zhong, C. Shen, Y. You, J. Chu, X. Zou, X. Dong, Y. Jin, and J. Wang. Temperature-insensitive optical fiber two-dimensional micrometric displacement sensor based on an in-line Mach–Zehnder interferometer. *J. Opt. Soc. Am. B*, 2012. 29(5):1136-1140.

[55] J.Chen, J.Zhou, and Z. Jia. High-Sensitivity Displacement Sensor Based on a Bent Fiber Mach-Zehnder Interferometer. *IEEE Photonics Technology Letter*, 2013. 25(23): 2354–2357.

[56] L. Yuan, J. Yang, Z. Liu, and J. Sun. In-fiber integrated Michelson interferometer. *Opt. Lett.,*2006. 31(18): 2692–2694.

[57] T. Li, A. Wang, K. Murphy, and R. Claus. White-light scanning fiber Michelson interferometer for absolute position – distance measurement. *Opt. Lett.,*1995. 20(7): 785–787.

[58] Q. Rong, X. Qiao, Y. Du, D. Feng, R. Wang, and Y. Ma. In-fiber quasi-Michelson interferometer with a core – cladding-mode fiber end-face mirror. *Applied Optics, 2013.* 52(7): 1441–1447.

[59] M. Bravo, A. M. R. Pinto, J. Kobelke, and K. Schuster. High precision micro-displacement fiber sensor through a suspended-core Sagnac interferometer. *Opt. Lett.,*2012. 37(2): 202–204.

[60] Huaping Gong; Haifeng Song; Sulei Zhang; Yongxing Jin; Xinyong Dong. Curvature Sensor Based on Hollow-Core Photonic Crystal Fiber Sagnac Interferometer. *Sensors Journal, IEEE,* 2014. 14(3):777-780.

[61] Pullteap, S.Development of an optical fiber based interferometer for small vibration measurements. *Optical Communications and Networks (ICOCN), 2012 11th International Conference.* Nov 28-30, 2012.1-4.

[62] Y. Rao. Recent progress in fiber-optic extrinsic Fabry – Perot interferometric sensors. *Optical Fiber Technology*, 2006. 12: 227–237.

[63] A. M. Rodrigues Pinto, J. M. Baptista, J. L. Santos, M. Lopez-Amo, and O. Frazão. Micro-displacement sensor based on a hollow-core photonic crystal fiber. *Sensors*, Jan 2012. 12: 17497–17503.

[64] M. Han and A. Wang. Exact analysis of low-finesse multimode fiber extrinsic Fabry – Perot interferometers. *Applied Optics*,2004. 43(24): 4659–4666, 2004.

[65] Q. Wu, J. Yuan, C. Yu, X. Sang, L. Sun, J. Li, T. Guo, and B. Guan. UV exposure on a single-mode fiber within a multimode interference structure. *Opt. Lett.*, 2014. 39(22): 6521–6524.

[66] M. Y. Mohd Noor, a. I. Azmi, a. S. Abdullah, a. S. Mohd Supa'at, N. Mohd Kassim, M. H. Ibrahim, and N. H. Ngajikin. High Sensitivity of Balloon-Like Bent MMI Fiber Low-Temperature Sensor. *IEEE Photonics Technol. Lett.*, 2015. 27(18): 1989–1992.

[67] R. Selvas. Wavelength tuning of fiber lasers using multimode interference effects. *Optics Express*, 2005. 13(23): 9439–9445.

[68] S. N. D. L. Garza and N. León. Widely tunable erbium-doped fiber laser based on multimode interference effect. *Optics Express*, 2010. 18(2): 2547–2549.

[69] W. S. Mohammed, A. Mehta, and E. G. Johnson. Wavelength Tunable Fiber Lens Based on Multimode Interference. *Journal of Lightwave Technology*, 2004. 22(2): 469–477.

[70] Ngajikin, N.H.; Daud, N.M.; Mohamed, N.; Awang, M.; Ismail, N.I..Coupling loss analysis in fiber tip lens and Micro Fabry Perot Multiplexer and demultiplexer connection. *Photonics (ICP), 2013 IEEE 4th International Conference.* Oct 28-30, 2013. 178-180.

[71] J. T. Costa and M. G. Silveirinha. Macroscopic Electromagnetic Response of Arbitrarily Shaped Spatially Dispersive Bodies formed by Metallic Wires. *Phys. Rev. B*, 2012. 86(7): 075129.

[72] S. A. Khan. Coordinate Geometric Approach to Spherometer. *Bulletin of the IAPT*, 2013. 5(6): 139-142. Available at: arXiv:1309.1951v1[physics.gen-ph]

[73] R. Islam, M. M. Ali, M. Lai, and K. Lim. Chronology of Fabry-Perot Interferometer Fiber-Optic Sensors and Their Applications: A Review. *Sensors*, 2014. 14: 7451–7488.

[74] J. Chandrappan, Z. Jing, R. V Mohan, P. O. Gomez, T. A. Aung, X. Yongfei, P. V Ramana, J. Lau, H. Shing, J. Chandrappan, Z. Jing, R. V Mohan, P. O. Gomez, A. Aung, X. Yongfei, P. V Ramana, J. Lau, H. Shing, and D. L. Kwong. Cost effective optical coupling for polymer optical fiber

communication. *Photonics Packaging, Integration, and Interconnects VIII, Proc. of SPIE*, 2008. 6899, 68991A:1-6.

[75] C. T. Ien, Y. L. Ai, T. D. M. Ilster, and H. D. S. Hieh. Design and Fabrication of Fiberlenses for Optical Recording Applications. *Jpn. J. Appl. Phys.*, 2002. 41(Part 1 3B): 1834–1837.

[76] A. A. Jasim, A. Z. Zulkifli, M. Z. Muhammad, S. W. Harun, and H. Ahmad. A new compact micro-ball lens structure at the cleaved tip of microfiber coupler for displacement sensing. *Sensors Actuators A. Phys.*, 2013. 189: 177–181.

[77] Y. K. Cheong, K. S. Lim, W. H. Lim, W. Y. Chong, R. Zakaria, Y. K. Cheong, K. S. Lim, W. H. Lim, W. Y. Chong, R. Zakaria, and H. Ahmad. Note : Fabrication of tapered fibre tip using mechanical polishing method. *Rev. Sci. Instrum.*, 2011. 82:086115.

[78] S. Yakunin and J. Heitz. Microgrinding of lensed fibers by means of a scanning-probe microscope setup. *Applied Optics*, 2009. 48(32): 6172-6177.

[79] S. Kohri, T. Tajikawa, and K. Ohba. Development of a Miniaturized Fiber-optic LDV Sensor for Local Blood Velocity Measurement. *Biomed. Eng. Res.*, 2013. 2: 131–138.

[80] K. Shiraishi, M. Kagaya, K. Muro, H. Yoda, Y. Kogami, and C. S. Tsai. Single-mode fiber with a plano-convex silicon microlens for an integrated butt-coupling scheme. *Appl. Opt.*, Nov 2008. 47(34): 6345-6349.

[81] A. Werber and H. Zappe. Tunable microfluidic microlenses. *Appl. Opt.*, 2005. 44(16): 3238-3245.

[82] G. Bai, Y. H. Tsang, K. L. Jim, and X. Zhang. UV-curable liquid-core fiber lenses with controllable focal length. Optics Express, 2013. 21(5): 22993–22998.

[83] Jiang Y, Tang C. High-finesse micro-lens fiber-optic extrinsic Fabry-Perot interferometric sensors. *Smart Mater. Struct.*, 2008. 17, 055013: 1-6

[84] J. Pietarinen, V. Kalima, T. T. Pakkanen, and M. Kuittinen. Improvement of UV-moulding accuracy by heat and solvent assisted process. *Microelectron. Eng.*, 2008. 85(2): 263–270.

[85] J.-M. Lopez-Hignera, M. a. Morante, and a. Cobo. Simple low-frequency optical fiber accelerometer with large rotating machine monitoring applications. *J. Light. Technol.*, 1997. 15(7): 1120–1130.

[86] Norland Products Inc. *Norland Optical Adhesive 61*. 2014.

[87] Norland Products Inc. Material Safety Data Sheet (MSDS) Norland optical adhesive 61. Cranbury, NJ (USA). Jan 12, 2015.

[88] G. Frigyes, E. Myers and J. Allison. *Fundamentals of Photoelectric Sensors*. Available at automation.com.

[89] K. Iizuka. *Elements of Photonics, In Free Space and Special Media*, vol. 1. John Wiley & Sons, 2002.

[90] P. G. Jia and D. H. Wang. Self-calibrated non-contact fibre-optic Fabry–Perot interferometric vibration displacement sensor system using laser emission frequency modulated phase generated carrier demodulation scheme. *Meas. Sci. Technol.*,2012. 23(11):115201.

[91] E. Cibula and D. Donlagic. Low-loss semi-reflective in-fiber mirrors. *Opt. Express*, 2010. 18(11): 12017–12026.

[92] L. R. Brow and U. Keller. Simple analytical expressions for the reflectivity and the penetration depth of a Bragg mirror between arbitrary media. *Optics Communications*, 1995. 116(4-6): 343–350.

[93] M. R. Hutsel and T. K. Gaylord. Inexpensive, efficient optical fiber end-face mirror. *Opt. Commun.*,2012. 285(17): 3608–3611.

[94] J.-N. Wang and J.-L. Tang. Photonic crystal fiber Mach-Zehnder interferometer for refractive index sensing. *Sensors*, 2012. 12(3): 2983–2995.

[95] E. J. Eklund and A. M. Shkel. Performance Tradeoffs in MEMS Sensors with High-Finesse Fabry-Perot Interferometry Detection. *NSTI-Nanotech*, 2005. 3(1): 533–536.

[96] P. B. Johnson and R.W. Christy. Optical Constants of the Noble Metals. *Phys. Rev. B*, 1972. 6: 4370-4379. Available at refractiveindex.info

[97] Nor Hafizah Ngajikin. *Microelectromechanical system floating-fabry perot optical tunable filter*. Ph.D. Thesis. Universiti Teknologi Malaysia, 2011.

[98] J. A. Marshall. *Measuring Copper Surface Roughness for High Speed Applications*. MacDermid Inc. Waterbury Ct, USA.

[99] M.P Vogler, X.Liu, S.G. Kapoor, R.E DeVor, and K.F. Ehmann. Development of meso-scale machine tool (mMT) systems. *Technical paper (MS), Society of Manufacturing Engineers*, 2002. MS02-181, pp 1-9.

[100] H.Qu, G.F. Yan, and M. Skorobogatiy. Interferometric fiber-optic bending/ nano-displacement sensor using plastic dual-core fiber. *Opt.Lett.*, 2014. 39: 4835-4838.