DETECTION OF WATER FLOW MOVEMENT IN OIL FIELD BY NANOCOATED POLYCARBONATE OPTICAL FIBRE SENSOR

MOHD SHAHRIZAN BIN MOSLAN

UNIVERSITI TEKNOLOGI MALAYSIA

DETECTION OF WATER FLOW MOVEMENT IN OIL FIELD BY NANOCOATED POLYCARBONATE OPTICAL FIBRE SENSOR

MOHD SHAHRIZAN BIN MOSLAN

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy

School of Chemical and Energy Engineering
Faculty of Engineering
Universiti Teknologi Malaysia

NOVEMBER 2021

ACKNOWLEDGEMENT

In the Name of Allah, the Merciful, the Beneficent. Praise be to the Lord of all worlds. Prayers and peace be upon our Prophet, Muhammad (SAW), his family and all of his companions. Alhamdulillah, all the praises and thanks be to Allah S.W.T for all Your blessing, for the strength You give me each day to complete this project and letting me live to complete this thesis.

I want to take this opportunity to thank all those people, who by enthusiasm or help in any way made this thesis possible. They have supported me towards my understanding particularly, my deepest appreciation to my main supervisor Prof. Ts. Dr. Mohd Hafiz Dzarfan Bin Othman for the unconditional support during my PhD study and research. Thank you for your motivation, enthusiasm, patience, immense knowledge and always have faith in me. My special thanks to my co-supervisor, Prof. Datuk Dr Ahmad Fauzi Bin Ismail, for the encouragement, guidance, advice, and ideas.

I am also indebted to Universiti Teknologi Malaysia (UTM) for funding my Ph.D study as well as financial support from Petroleum Research Fund under Alpha Matrix project. Fellow staffs and technician of Advanced Membrane Technology Research Centre (AMTEC) also deserve special thanks for their assistance in completing my PhD journey. My sincere appreciation also extends to all my colleagues and others who have provided assistance at various occasions. Their views and tips are indeed useful. Unfortunately, it is not possible to list all of them in this limited space.

Above all, I would like to express my profound gratitude to my beloved mother and family members for their continuous love, support, motivation, and encouragement. They are indeed a source of inspiration to me. They all kept me going, and this thesis would not have been possible without them.

ABSTRACT

The use of chemical tracers for oil reservoir monitoring is important to provide assurance and maximise production from mature fields. Nonetheless, this practice requires a huge amount of chemical, thus special consideration in regards of the technical, cost, and environmental aspects is necessary. Henceforth, a more efficient, real-time data acquisition technique to monitor the reservoir must be established. In recent times, fibre optic sensing technology has been touted as a reliable option to improve conventional method for reservoir monitoring. However, the use of conventional glass optical fibre is not favourable as it is fragile, hard to handle and vulnerable to hydrogen attack. Hence in this scenario, the use of polymer optical fibre is beneficial. Nonetheless, the polymer selection is crucial as it must withstand high operating temperature conditions. Therefore, this study focuses on the development of a robust polycarbonate-based polymer optical fibre (PCPOF) sensor to detect oil movement in porous media. Polycarbonate (PC) was chosen as the core as it possesses excellent thermal and optical properties and they are important criteria in fabrication of POF for high temperature condition. In the first stage of the study, the extrusion temperatures were varied from 250 to 310 °C and drawing speeds was manipulated from 5 to 20 rpm during the PC core fibre fabrication in order to obtain the most desired properties in terms of its diameter, pore-free structure and sufficient mechanical strength. It was discovered that the best extrusion temperature was at 290 °C in which at this temperature, the polymer was in a completely molten and exhibited excellent light propagation properties. Meanwhile, a drawing speed of 15 rpm produced a comparable fibre diameter of ~569 µm with a mechanical strength of 76.68 MPa. Subsequently, in the second stage, two sets of PC core fibres were fabricated with individual cladding materials based on polycarbonate/polymethyl methacrylate (PC/PMMA) blend and polymethyl pentane (PMP). Prior to the cladding layer fabrication, it was initially casted into thin films for its optical and thermal characterisation, and it was found that the ideal PC/PMMA ratio for cladding application was 80/20. At this composition, the PC/PMMA cladding exhibited a transparency of ~99 % and a glass transition temperature of 124.91 °C. On the other hand, the transparency of PMP was ~95 % and its transition temperature was 228.45 °C. Next, the cladding layer on the PC core was then fabricated via dip-coating technique. The prepared PC core with different claddings were evaluated to determine their power output. It was found that PMP cladding layer enhanced the performance of the PC core with an increment in power output by 60 % as compared to PC/PMMA cladded PC core which exhibited an increase of only 28.8 %. Due to excellent light propagation properties, the PMP cladded PCPOF was utilised to fabricate the sensor in the last phase. In the third stage, the sensor was fabricated via a multistage method involving plane-by-plane inscription, partial removal of cladding and TiO_2 deposition to enhance its sensing ability. The complete PCPOF sensor was tested at temperatures of 60 °C, 90 °C and 120 °C and its sensitivity was evaluated. Three central Bragg wavelengths of 750 nm, 800 nm and 850 nm were successfully inscribed on the PCPOF. Moving forward, the best etching time was found to be at 9 min by remaining ~1.47 µm of cladding thickness. Further increment of etching time may result in damage towards the fibre core. Then, TiO_2 was uniformly distributed on the sensing region via a double dip coating technique to ensure all sensing regions were covered with nanoparticles. On average, it was discovered that the sensitivity of sensor was more than ~100 nm/RIU in different test surrounding temperatures. The sensor also was able to operate at a surrounding temperature of 120 °C. In the oil displacement test, the sensor managed to detect oil/water flow inside the porous media by shifting its central wavelength when in contact with different liquid. These results show that utilising fibre optic sensor to detect oil movement within a porous media is feasible and can be further developed to create a functional alternative technology to continuously monitor reservoir to better understand reservoir fluid flow pathways.

ABSTRAK

Penggunaan penyurih kimia untuk pengawasan reservoir adalah penting bagi menjamin dan memaksimumkan pengeluaran dari medan matang. Walau bagaimanapun, amalan ini memerlukan jumlah bahan kimia yang banyak. Oleh itu, pertimbangan khas diperlukan dari segi teknikal, kos, dan persekitaran. Sehubungan itu, teknik perolehan data masa nyata yang lebih berkesan untuk memantau reservoir mesti diperkenal. Sejak kebelakangan ini, teknologi penderiaan gentian optik disebut sebagai pilihan yang boleh dipercayai untuk menambah baik kaedah konvensional bagi pemantauan reservoir. Walau bagaimanapun, penggunaan gentian optik kaca konvensional adalah tidak sesuai berikutan sifatnya yang rapuh, sukar dikendali dan rentan terhadap serangan hidrogen. Oleh itu, dalam senario ini, penggunaan gentian optik polimer bermanfaat. Walau bagaimanapun, pemilihan polimer adalah penting berikutan kemampuannya berfungsi pada suhu operasi yang tinggi. Oleh itu, kajian ini memberikan tumpuan terhadap pembangunan sensor gentian optik polimer berasaskan polikarbonat (PCPOF) untuk mengesan pergerakan minyak didalam media berliang. Polikarbonat (PC) dipilih sebagai teras kerana mempunyai sifat terma dan optik yang sangat baik, dan semuanya ialah kriteria penting dalam pembuatan POF untuk keadaan suhu tinggi. Pada peringkat pertama kajian, suhu penyemperitan diubah dari 250 °C hingga ke 310 °C dan halaju penggulungan ditingkatkan dari 5 rpm hingga ke 20 rpm semasa pembuatan gentian teras PC bagi memperoleh sifat yang paling dikehendaki dari segi diameter, struktur bebas berliang dan kekuatan mekanikal yang mencukupi. Suhu penyemperitan terbaik ialah 290 °C dengan pada suhu ini, polimer berada dalam keadaan lebur sepenuhnya dan menunjukkan sifat perambatan cahaya yang sangat baik. Sementara itu, halaju penggulungan 15 rpm menghasilkan diameter serat yang setanding ~ 569 µm dengan kekuatan mekanikal 76.68 MPa. Selepas itu, pada peringkat kedua, dua set gentian teras PC dibuat dengan bahan penyalut individu berdasarkan campuran polikarbonat/polimetil metakrilat (PC/PMMA) dan polimetil pentana (PMP). Sebelum bermulanya penyalutan, penyalut dihasilkan dalam bentuk selaput tipis untuk pencirian optik dan termalnya dengan nisbah unggul untuk PC/PMMA bagi pengaplikasian penyalutan ialah 80/20. Pada komposisi ini, penyalut PC/PMMA memperlihatkan sifat lut sinar ~ 99% dengan suhu peralihan kaca 124.91 ° C. Sebaliknya, lut sinar bagi PMP ialah ~ 95% dengan suhu peralihannya ialah 228.45 ° C. Seterusnya, penyalutan pada teras PC dihasilkan menerusi kaedah penyalutan celup. Teras PC dengan salutan yang berlainan dinilai bagi menentukan output kuasa masing-masing. Penyalut PMP didapati berjaya meningkatkan prestasi teras PC dengan peningkatan output kuasa sebanyak 60 % berbanding teras PC bersalut PC/PMMA yang hanya meningkatkan 28.8 %. Berikutan sifat perambatan cahayanya yang sangat baik, PCPOF bersalut PMP telah diguna untuk menghasilkan sensor pada fasa terakhir. Pada peringkat ketiga, sensor dihasilkan menerusi beberapa tahap yang melibatkan penggores ukiran satah-demi-satah, penyingkiran separuh penyalut, dan pengendapan TiO_2 bagi meningkatkan kemampuan penderiaan. Sensor PCPOF lengkap diuji pada suhu 60 °C, 90 °C, dan 120 °C dengan kepekaannya dinilai. Tiga panjang gelombang Bragg pusat 750 nm, 800 nm, dan 850 nm berjaya digores ukir pada PCPOF. Melangkah ke hadapan, masa punaran terbaik ialah 9 min dengan meninggalkan ~1.47 µm ketebalan penyalut. Peningkatan masa punaran selanjutnya boleh mengakibatkan berlakunya kerosakan pada teras gentian. Kemudian, TiO_2 disebarkan secara seragam pada kawasan penderian menerusi teknik penyalutan celup berganda bagi memastikan semua kawasan penderia disaluti partikel nano. Secara purata, kepekaan sensor didapati melebihi ~ 100 nm/RIU pada suhu ujian yang berlainan. Sensor turut mampu beroperasi pada suhu sekitar 120 °C. Dalam ujian penyesaran minyak, sensor berjaya mengesan aliran minyak/air di dalam media berliang dengan menganjakkan panjang gelombang pusatnya ketika bersentuhan dengan cecair berlainan. Hasil ini menunjukkan bahawa penggunaan sensor gentian optik untuk mengesan pergerakan minyak didalam media berliang boleh dilaksana dan seterusnya mampu dikembang bagi menghasilkan teknologi alternatif berfungsi untuk memantau reservoir secara berterusan supaya lebih memahami laluan aliran bendalir.

TABLE OF CONTENTS

	TITLE	PAGE
DECLARATION		**iii**
DEDICATION		**iv**
ACKNOWLEDGEMENT		**v**
ABSTRACT		**vi**
ABSTRAK		**vii**
TABLE OF CONTENTS		**viii**
LIST OF TABLES		**xii**
LIST OF FIGURES		**xiii**
LIST OF ABBREVIATIONS		**xviii**
LIST OF SYMBOLS		**xx**
LIST OF APPENDICES		**xxi**
CHAPTER 1	**INTRODUCTION**	**1**
1.1	Background of Study	1
1.2	Problem Statement	5
1.3	Objectives of Study	7
1.4	Scope of Study	8
1.5	Significance of Study	9
1.6	Thesis Organisation	10
CHAPTER 2	**LITERATURE REVIEW**	**13**
2.1	Introduction	13
2.2	Downhole Monitoring Techniques	13
	2.2.1 Tracer and Fluid Injections	14
	2.2.2 Downhole Seismic Sensors	15
	2.2.3 Streaming Potential Measurement	17
	2.2.4 Fibre Optic Sensors	18
2.3	Overview on Optical Fibre	25
	2.3.1 Operation Principle of Optical Fibre	26

		2.3.2 Type of Optical Fibre	27
	2.4	Application of Polymer Optical Fibre	29
	2.5	Overview on Polymer Optical Fibre Core Material	32
	2.6	Fabrication Method for Polymer Optical Fibre Core	35
	2.7	Overview on Polymer Optical Fibre Cladding Material	38
	2.8	Overview on Polymer Blending	41
	2.9	Structural and Mechanical Properties of Optical Fibre	44
	2.10	Optical Properties of Optical Fibre	48
	2.11	Fibre Optic Sensor	50
		2.11.1 Basic Principle of Fibre Optical Sensor	50
		2.11.2 Application of Fibre Optic Sensor	51
		2.11.3 Polymer Optical Fibre Bragg Grating Sensor	53
		2.11.4 Fabrication Techniques of Polymer Optical Fibre Bragg Gratings	57
		2.11.5 Nanocoated Fibre Optic Sensor	60
	2.12	Research Gap	65
CHAPTER 3		**RESEARCH METHODOLOGY**	**67**
	3.1	Introduction	67
	3.2	Materials	69
	3.3	Fabrication of Polymer Optical Fibre Core	70
		3.3.1 Polymer Drying Process	70
		3.3.2 Extrusion of The Polymer Optical Fibre Core	71
	3.4	Fabrication of PC/PMMA and PMP Flat Sheet Cladding Film	72
	3.5	Fabrication of PCPOF cladding Via Dip-coating Technique	73
	3.6	Fabrication of Polycarbonate Sensor Layer	74
		3.6.1 Inscription of FBG on the Polycarbonate Optical Fibre	74
		3.6.2 Removal of the PCPOF Cladding by Etching Process	75
		3.6.3 Deposition of Titanium Dioxide Nanoparticles on the PC FBG	75
	3.7	Characterisation Methods	77

3.7.1	Morphological Analysis	78
3.7.2	Fourier Transform Infra-red Spectroscopy	78
3.7.3	X-Ray Diffraction Analysis	78
3.7.4	Thermal Gravimetric Analyzer	79
3.7.5	Differential Scanning Calorimetry	79
3.7.6	UV-Vis-NIR Spectroscopy	79
3.7.7	Mechanical Properties	80
3.7.8	Optical Loss	80
3.8	POF Sensor for Detection of Oil Flow Movement	81
3.8.1	Measurement of the Sensitivity for the POF Sensor	81
3.8.2	Porosity and Permeability Measurement	82
3.8.3	Measurement of Oil Flow Movement in Porous Media at High Temperature	84
CHAPTER 4	**POLYCARBONATE BASED OPTICAL FIBRE CORE**	**87**
4.1	Introduction	87
4.2	The Effect of Extrusion Temperature	88
4.2.1	Optical Properties of the Polycarbonate Fibre Core	88
4.2.2	Thermal Properties of the Polycarbonate Fibre Core	92
4.3	The Effect of Collector Speed	94
4.3.1	Structural Properties of the Polycarbonate Fibre Core	94
4.3.2	Mechanical Properties of the Polycarbonate Fibre Core	95
4.4	Conclusion	97
CHAPTER 5	**PC/PMMA BLEND AND PMP AS A CLADDING MATERIAL FOR PC OPTICAL FIBRE CORE**	**99**
5.1	Introduction	99
5.2	Polycarbonate/Polymethyl Methacrylate Cladding: The effect of polymer ratio	100
5.2.1	Optical Properties of PC/PMMA Composite	100

5.2.2 Thermal Properties of PC/PMMA Composite 105

5.3 Polymehtylpentene Cladding 108

5.3.1 Optical Properties of Polymethylpentene 108

5.3.2 Thermal Properties of Polymethylpentene 109

5.4 Comparison Between PC/PMMA and PMP Cladded PCPOF 111

5.4.1 Mechanical Properties of PC Core With PC/PMMA and PMP Cladding 111

5.4.2 Morphology of PC core with PC/PMMA and PMP cladding 112

5.5 Comparison Between PC/PMMA and PMP Cladded PCPOF: Optical Performance 114

5.6 Conclusion 115

CHAPTER 6 POLYMER OPTICAL FIBRE SENSOR FOR DETECTTION OF OIL FLOW MOVEMENT INSIDE POROUS MEDIA 117

6.1 Introduction 117

6.2 Characteristics of Polycarbonate Optical Fibre Sensor 118

6.2.1 Morphology of Partially Removed Cladding layer by Etching Process 118

6.2.2 Properties of Deposited TiO_2 on the PCPOF 120

6.2.3 TiO_2 Deposition Mechanism on PC Fibre Optic Surface 125

6.3 Sensitivity Measurement of The Sensor 127

6.4 Detection of Oil Flow Movement in Porous Media 136

6.5 Conclusion 142

CHAPTER 7 CONCLUSIONS AND RECOMMENDATION FOR FUTURE WORKS 143

7.1 Conclusion 143

7.2 Recommendation for Future Work 145

REFERENCES 149

APPENDIX A - D 171 - 174

LIST OF PUBLICATIONS 175

LIST OF TABLES

TABLE NO.	TITLE	PAGE
Table 2.1	In-well pioneer project for the fibre optic deployment (Kragas *et al.*, 2001)	21
Table 2.2	Field trial of fibre optic sensor	22
Table 2.3	Comparison between different downhole monitoring device	24
Table 2.4	Summary of selected polymer optical fibre materials	35
Table 2.5	Comparison of optical properties for few type of polymer optical fibre (Zubia and Arrue, 2001)	49
Table 2.6	Summary of nanocoated fibre optic sensor	64
Table 3.1	List of materials used for fabrication of POF	69
Table 3.2	Extrusion condition for the polymer optical fibre core	72
Table 3.3	Composition for preparation of cladding solution	73
Table 3.4	Summary of characterisation	77
Table 3.5	Description of the glass bead pack model	84
Table 4.1	Infrared attribution of absorbance peaks	91
Table 4.2	The effect of collector speed on the mechanical properties of the PC core fibre	96
Table 5.1	Refractive index of PC/PMMA cladding at different composite ratio	101
Table 5.2	Transmittance of PC/PMMA composite measured at 550 nm	103
Table 5.3	Glass transition temperature for the PC/PMMA composites	108
Table 5.4	The effect of different cladding material on the mechanical strength of PC-POF	112
Table 6.1	Oil/water concentration and its respective refractive index	127
Table 6.2	Summary of the sensitivity of the PC POFBG	135

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
Figure 1.1	Publication on optical fibre-based sensor (source from Scopus analysis as of April 2021)	3
Figure 1.2	Schematic diagram of a polymer optical fibre sensor	4
Figure 2.1	Principle of fibre optic DTS (Yamate, 2008)	19
Figure 2.2	Overview of flow monitoring principle using fibre optic DAS system (Fidaner, 2017)	20
Figure 2.3	Installation of first optic Bragg grating sensor in Bakerfield, California (Bostick, 2003)	23
Figure 2.4	Assembly of fibre optic Bragg grating sensor for flowmeter, pressure and temperature measurement (Kragas *et al.*, 2002)	23
Figure 2.5	Basic structure of an optical fibre	25
Figure 2.6	Total internal reflection inside optical fibre	26
Figure 2.7	Physical configuration of a fibre (a) single-mode fibre; (b) multi-mode fibre (Ahamed, 2013)	28
Figure 2.8	Schematic diagram of single-mode and multi-mode step index optical fibre and multi-mode graded-index optical fibre (Fidanboylu and Efendioglu, 2009)	29
Figure 2.9	Worldwide polymer optical fibre market as of 2020 (IGI Consulting Incorporation)	30
Figure 2.10	Market of fibre optic by application (Kröplin *et al.*, 2017)	30
Figure 2.11	Fibre optic market by region (Kröplin *et al.*, 2017)	32
Figure 2.12	Schematic diagram for continuous process for fabrication of polymer optical fibre (Beckers *et al.*, 2017)	36
Figure 2.13	Melt spinning with subsequently rapid cooling in water quench (Bunge *et al.*, 2014)	38

Figure 2.14	Example of designs of optical fibre (a) hollow core microstructured optical fibre (Humbert *et al.*, 2004); (b) single mode microstructured optical fibre (Argyros, 2009); (c) high bandwidth microstructured optical fibre (Argyros, 2009); (d) solid core optical fibre (Rioux *et al.*, 2017)	46
Figure 2.15	Typical curve stress-strain for optical fibre (Arrospide *et al.*, 2017)	46
Figure 2.16	Intrinsic loss of common polymer optical fibre (Peters, 2011)	48
Figure 2.17	Component for fibre optic sensor system (Fidanboylu and Efendioglu, 2009)	50
Figure 2.18	Fibre optic sensor type (Fidanboylu and Efendioglu, 2009)	51
Figure 2.19	Fibre optic sensor by measurand (Lee, 2003)	52
Figure 2.20	Fibre optic sensor type (Lee, 2003)	52
Figure 2.21	Illustration of the FBG sensor (Jin and M Granville, 2016)	53
Figure 2.22	Some experimental implementations of embedded POFBGs (Broadway, Min, *et al.*, 2019)	55
Figure 2.23	Illustration for the POFBG inscription setup (Marques *et al.*, 2018)	59
Figure 3.1	Research design flowchart	68
Figure 3.2	Polymer drying hopper	70
Figure 3.3	Schematic diagram of the single screw extruder for fabrication of POF core using melt spinning technique	71
Figure 3.4	Schematic diagram for the preparation of the cladding film	72
Figure 3.5	Schematic diagram of dip-coating process for fabrication of cladding layer on PC core fibre	74
Figure 3.6	Femtosecond laser FBG inscription setup illustration	75
Figure 3.7	Schematic diagram for deposition of TiO_2 process on POF	76
Figure 3.8	Schematic design for the TiO_2 deposited onto the PC FBG sensor	76

Figure 3.9	Experimental setup for determination of power output	81
Figure 3.10	Schematic diagram for the refractive index sensor experimental setup	82
Figure 3.11	Schematic diagram for the glass bead pack model	83
Figure 3.12	Experimental setup for detection of oil migration inside porous media	85
Figure 4.1	Normalised absorbance spectra for polycarbonate fibre core extruded at different temperature	88
Figure 4.2	Infrared absorption spectra for the PC fibre core fabricated at different extrusion temperature	90
Figure 4.3	Light propagation analysis for the PC core fibres at different extrusion temperature. Inset graph is the power output for PC core fibre extruded at 310 °C	92
Figure 4.4	Weight loss percentage of PC fibre extruded at different temperature. Inset graph is the T_{onset} for all the PC fibre samples	93
Figure 4.5	Cross-section of PC optical fibres extruded at different collector speed; a) 5 rpm; b) 10 rpm; c)15 rpm; d) 20 rpm	95
Figure 4.6	Stress-strain curve for PC core fibre extruded at 20 rpm	97
Figure 5.1	Transmittance spectra of the composite at different PC/PMMA ratio	102
Figure 5.2	Illustration of the polymer chain rearrangement for the PC and PMMA composite	103
Figure 5.3	XRD pattern of PC/PMMA blend at various ratio	104
Figure 5.4	Infrared transmission spectrum for PC/PMMA composites	105
Figure 5.5	Weight loss curve for PC/PMMA composite. Insert graph is the onset temperature for the composite	106
Figure 5.6	DSC thermograms for neat PC and PC/PMMA composites at different ratio	107
Figure 5.7	Transmittance spectra of PMP	109
Figure 5.8	Weight loss curve for PMP	110

Figure 5.9	DSC thermograms for PMP	111
Figure 5.10	SEM images of the optical fibre with different cladding (a) 80/20 PC/PMMA cladding; (b) PMP cladding	113
Figure 5.11	Effect of cladding material on the power output	115
Figure 6.1	Cross section SEM images of the PC POF at different etching time	119
Figure 6.2	Effect of etching time on the propagation loss of PCPOF	120
Figure 6.3	Surface SEM image of PC POF fibre (a) before coating; (b) after TiO_2 coating; (c) magnified SEM image of TiO_2 coating	121
Figure 6.4	Atomic force microscopic images of PC fibre optic sensor (a) before TiO_2 coating; (b) after TiO_2 coating	122
Figure 6.5	Energy dispersive X-ray spectroscopy analysis	123
Figure 6.6	X-ray diffraction pattern of the PC fibre optic surface before and after coating with TiO_2	124
Figure 6.7	Surface modification of TiO_2 by APTES	125
Figure 6.8	Mechanism of TiO_2 deposition on polymer optical fibre surface	126
Figure 6.9	Illustration of working principle for the TiO_2 coated FBG sensor	128
Figure 6.10	PC POFBG spectrum in different refractive index medium tested at different surrounding temperature	132
Figure 6.11	Sensitivity analysis graph for the PC POFBG at different surrounding temperature (a) 750 nm; (b) 800 nm; (c) 850 nm	134
Figure 6.12	(a)Reflection spectrum after the model was saturated with oil; (b) Illustration of oil saturated glass bead model	136
Figure 6.13	(a) Reflection spectrum after injection of 0.25 PV brine; (b) Illustration of oil/water movement after 0.25 PV bine injection	137
Figure 6.14	(a) Reflection spectrum after injection of 0.50 PV brine; (b) Illustration of oil/water movement after 0.50 PV bine injection	138

Figure 6.15	(a) Reflection spectrum after injection of 0.75 PV brine; (b) Illustration of oil/water movement after 0.75 PV bine injection	139
Figure 6.16	(a) Reflection spectrum after injection of 1.00 PV brine; (b) Illustration of oil/water movement after 1.00 PV bine injection	140
Figure 6.17	(a) Reflection spectrum after injection of 1.25 PV brine; (b) Illustration of oil/water movement after 1.25 PV bine injection	141

LIST OF ABBREVIATIONS

AFM	-	Atomic Force Microscopy
APTES	-	3-Aminopropyl-Triehtoxysilane
ATR-IR	-	Attenuated Total Reflection-Infrared
AVO	-	Amplitude Variation with Offset
AZO	-	Aluminium doped Zinc Oxide
$CaCl_2$	-	Calcium Chloride
CYTOP	-	Cyclic Transparent Olefins Polymer
COC	-	Cyclic Olefin Copolymers
COPE	-	Copoly(ether-ester)
DEGDAC	-	Diethylene Glycol Di(Allyl Carbonate)
DTS	-	Distributed Temperature Sensing
DAS	-	Distributed Acoustic Sensing
DCM	-	Dichloromethane
DSC	-	Differential Scanning Calorimetry
EDX	-	Energy Dispersive X-Ray
EOR	-	Enhanced Oil Recovery
ESD	-	Electronic Sensor Device
EVA	-	Ethylene Vinyl Acetate
FA	-	Fluoroacrylate
FAWAG	-	Foam Assisted Water Alternate Gas
FBG	-	Fibre Bragg Grating
FESEM	-	Field Emission Scanning Electron Microscope
FTIR	-	Fourier Transform Infrared
GOF	-	Glass Optical Fibre
HFP	-	Hexafluoro Propene
HSE	-	Health, Safety and Environment
IOR	-	Improved Oil Recovery
ITO	-	Indium Tin Oxide
LAN	-	Local Area Network
LED	-	Light-emitting Diode

MMF	-	Multimode Fibre
MOST	-	Media Oriented Systems Transport
NA	-	Numerical Aperture
NaCl	-	Sodium Chloride
OSA	-	Optical Spectrum Analyser
PC	-	Polycarbonate
PMMA	-	Polymethyl Methacrylate
POF	-	Polymer Optical Fibre
PMP	-	Polymethyl Pentene
RIU	-	Refractive Index Unit
RPM	-	Revolution Per Minute
SMF	-	Single Mode Fibre
TiO_2	-	Titanium Dioxide
TGA	-	Thermogravimetric Analysis
TFBG	-	Tilted Fibre Bragg Grating
UV	-	Ultraviolet
VDF	-	Vinylidene Fluoride
VSP	-	Vertical Seismic Profiling
VSEP	-	Vertical Seismoelectric Profiling
WAG	-	Water Alternating Gas
XRD	-	X-Ray Diffraction

LIST OF SYMBOLS

n_1	-	Refractive Index of The Core
n_2	-	Refractive Index of The Cladding
P_{out}	-	Power Output
P_{in}	-	Power Input
Ø	-	Porosity
PV	-	Pore Volume
BV	-	Bulk Volume
k	-	Permeability
Q	-	Injection Flowrate
µ	-	Viscosity of Injected Fluid
L	-	Length of Linear Model
A	-	Cross Section Area of Linear Model
∆P	-	Pressure Difference
MPa	-	Mega Pascal
GPa	-	Giga Pascal
cm	-	Centimetre
°C	-	Degree Celsius
ppm	-	Part Per Million
%	-	Percentage
T_{onset}	-	Onset Degradation Temperature
µm	-	Micrometre
E	-	Young’s modulus
T_g	-	Glass Transition Temperature

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
APPENDIX A	Partially removed cladding layer by chemical etching process	171
APPENDIX B	Optical properties of TiO_2 nanoparticles	172
APPENDIX C	Porosity and permeability calculation	173
APPENDIX D	Calibration curve for oil/water concentration	174
APPENDIX E	List of publications	175

CHAPTER 1

INTRODUCTION

1.1 Background of Study

World’s energy demand continues to increase due to industrial activities in both developed and developing countries. For majority of the globe, fossil fuel energy sources such as natural gas, and oil are the commodity in producing energy (Zhang and Yang, 2018). Though coronavirus disease 2019 (COVID-19) has been punching the world and causes the demand for energy decline by 6 % in 2020 (Jiang *et al.*, 2021), oil still shared the biggest energy matrix with 33.1 % from the total energy consumption in 2020 (British Petroleum, 2020). In spite of the slower production pace, hydrocarbon especially oil and gas demand is still high in most of the continents in the world and remain as the major source of energy fuelling the world economy by 2035 (British Petroleum, 2017). Current world oil production mostly comes from mature field and over the past decade oil producing companies are maximizing the oil production from these fields as the exploration and development of new field requires millions of dollars and is very challenging. However, stagnant oil production and unimpressive recovery by primary and secondary recovery have made the situation more precarious. Therefore, advanced technologies are necessary in order to meet the energy demand in many more years to come. Ordinarily, maximum total oil recovery by primary and secondary recovery stage is roughly around 20 % to 40 % (Muggeridge *et al.*, 2013). The remaining oil trapped in the reservoir is the aim of the advanced method which have become known as Improved Oil Recovery (IOR) and Enhanced Oil Recovery (EOR). Optimization of oil production by scrutinizing the third oil recovery or EOR is necessary because the remaining oil trapped in the reservoir is due to the higher oil viscosity, high capillary forces, high interfacial tension and thus it requires more advanced approaches to migrate the oil to the production well.

Various techniques have been investigated for EOR and IOR such as miscible gas injection, water alternating gas (WAG) injection, polymer flooding, steam injection, hydraulic fracturing, scale inhibition treatment and acid stimulation treatment. IOR and EOR term may be used synonymously which the ultimate goal is to produce more oil via better engineering and project management approach such as identifying the volume of oil remain in the reservoir (Muggeridge *et al.*, 2013). Reservoir monitoring study during the EOR processes is crucial in oil industry as it provides important data to the experts to maximize oil recovery and also to improve the planning for future continuation of production cycles (Djuraev *et al.*, 2017). An excellent monitoring study during the oil production is capable to record the saturation changes in the reservoir, measuring the fluid location and can predict the distribution of the fluids in the reservoir, subsequently this can dictate the success of enhanced oil recovery processes (Djuraev *et al.*, 2017).

There are quite a number of reservoir monitoring techniques such as tracer injection (Dezabala *et al.*, 2011; Cubillos *et al.*, 2007; Cubillos *et al.*, 2006), multifunctional downhole sensor (Saunders *et al.*, 2008) and well fall-off test (Orangi and Ershaghi, 2008). Each choice of monitoring techniques is designed for specific applications and it depends on various factors such as accuracy, consistency, cost effectiveness, and installation procedures. Application of tracer in the reservoir system has been applied in many part of the world for reservoir monitoring to monitor and retrieve flow parameters (Jaafar *et al.*, 2014). However, the usage of tracer requires a huge amount of chemical that need to be injected into the reservoir formation and it also requires much testing. A high amount of tracer implies special consideration of technical, cost and environmental aspect are needed (Cubillos et al., 2006). Furthermore, the analytical technique used to analyse the tracer require a more advanced technology as well as increased the need for more skilled personnel to perform the analysis (Dyrli and Leung, 2017). Furthermore, since the tracer is injected into the reservoir, engineers need to wait for the tracer to come out at the producing well and this process takes a long time. An improved and more promising approach is by using fibre optic sensor as an alternative technology for reservoir monitoring provides the option of real time data acquisition besides can save time and cost (Chen et al., 2018).

A good monitoring technique is crucial in developing a coherent reservoir management strategy to minimize all the reservoir uncertainties during oil production. One of the technologies that can be utilized in reservoir monitoring is fibre optic sensor. This sensor can detect the presence and absence of an analyte and the research on fibre optic sensor has been increasing for the past 10 years as shown in Figure 1.1.

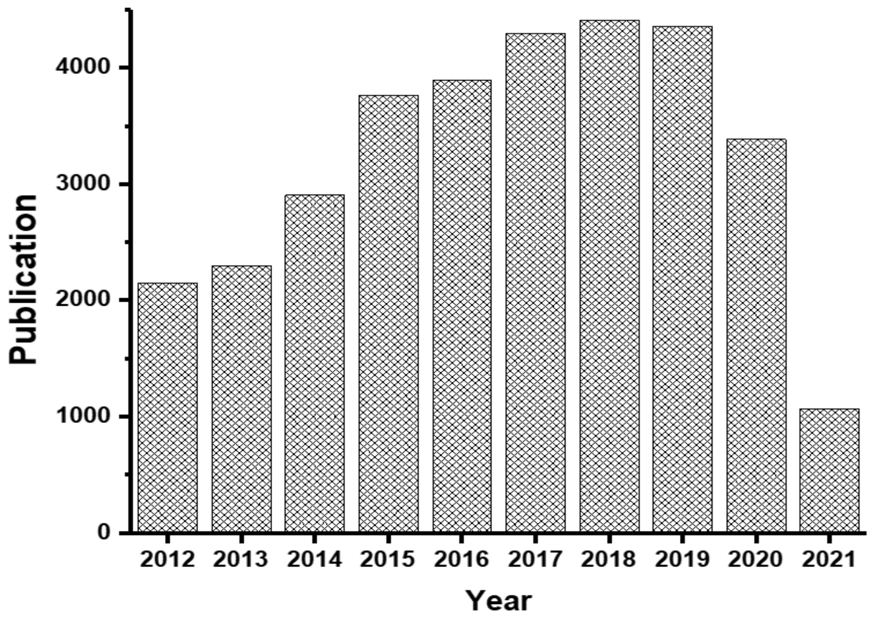

Figure 1.1 Publication on optical fibre-based sensor (source from Scopus analysis as of April 2021)

In petroleum engineering particularly, the use of fibre optic sensor is very interesting. The fibre optic sensor principle is simple in which a light is sent through a fibre optic from the surface to a sensor downhole. When the sensor detects any external quantity, it will modulate the light beam and the measurand is detected by comparing the reflected light beam with the original light beam at the surface. The industry as a whole recognizes the need for the improved monitoring system and optical fibre-based sensor is seen to be the key component of the expansion which allowing the company to leverage the advantages offered by optical fibre while improving operational performance and accuracy.

Polymer optical fibre (POF) have been around for many years and it shares most of the benefits of conventional glass optical fibre such as sensitive to electromagnetic waves, low weight, small dimension and low intrusiveness (Muto *et al.*, 2003). In addition to that, optical fibre sensor offers additional important characteristic that it does not produce any fire spark during operation. As the environment in the reservoir is very flammable and the space is relatively small, fibre optic sensors can be utilised in this environment and makes it a very good candidate to be used in reservoir monitoring operation. A schematic diagram for an optical fibre sensor is shown in Figure 1.2. As shown in below, a fibre optic sensor mainly consists of 3 major component which are the core, cladding and sensing region. Hence, this study will be focusing on the fabrication and development of these major components. Fibre optic sensor works based on the principle that light from the light source is transmitted via an optical fibre which experiences change in its parameter in the optical fibre and reaches a detector which measures this change. An optical fibre consists of the core which has a higher refractive index than the cladding layer and acts based on the total internal reflection principle. The reflected light is transmitted to a sensor that convert the light energy into an electrical signal.

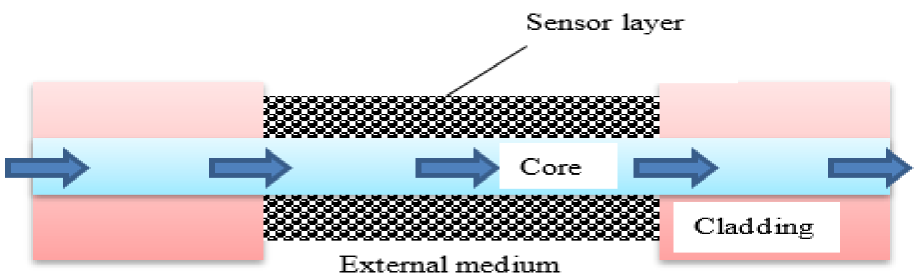

Figure 1.2 Schematic diagram of a polymer optical fibre sensor

Application of glass optical fibre (GOF) in downhole technology application is not favourable due to several factor. This is because just as its name, glass optical fibre is very subtle type of fibre as it has less resistant to flexibility and it has more chances of breakage if it is put at the insecure place. Due to that, glass optical fibres are always used in close environment. Besides that, the usage of glass optical fibre also is very expensive because of its fragility, it is hard to deploy and installation as well as termination of the glass optical fibre sensor need to be done by the specialist

(Berghmans and Thienpont, 2014). The application of glass optical fiber sensor in oil and gas also has its limitation which is the presence of hydrogen which come from free hydrogen gas (H_2) or hydroxyl compound in the reservoir may affect the silica based fiber which causing distortion or darkening of the fibre and reduce the accuracy of the measurement (Baldwin, 2014; Jacobs, 2014). During the fabrication of glass optical fiber, silica can form open structure as a results of ring orientation. This open structure may react with hydrogen and can cause finite attenuation to increase over the remaining service life of the fiber. The reaction of hydrogen with silica fiber also increased at elevated temperature. Therefore, due to these drawbacks, plastic optical fiber sensor is seen to be the best option to overcome these problems.

Poly (methyl methacrylate) (PMMA) is by far the most commonly used polymer for fabrication of the polymer optical fibre and one of the promising polymers to be used for the application in optical, pneumatic actuation, sensor and biomedical application (Ali *et al.*, 2015). However, there is a drawback of PMMA which is the glass transition of PMMA is relatively lower in which it cannot be used in high temperature condition. It is reported that the glass transition temperature (T_g) of PMMA is between 100 ℃ to 115 ℃ and the operating temperature of PMMA optical fibre is between -50 ℃ to 85 ℃ (Zhong *et al.*, 2016; Beckers *et al.*, 2015; Poomalai *et al.*, 2007). Beyond this temperature, some of the PMMA optical fibre's physical properties will change in which the optical fibre will lose its rigidity as well as its transparency. In addition to that the service span of the polymer optical fibre will reduce especially in humid conditions which accelerate the degradation of the polymer.

1.2 Problem Statement

Application of polymer optical fibre sensor in oil and gas industry requires a high resistant temperature material. This is because, generally hydrocarbon can be found at interval of above 6200 ft, and the reservoir temperature is around 190 °F or 90 ℃. In Malaysia, taking an example of Dulang field which located in Kuala Terengganu offshore is having reservoir temperature of 96 ℃ (Hussain et al., 1992). The use of PMMA is not favourable as it possesses a low thermal resistance and exhibit a poor performance in higher operating temperature. Thus, PC is seen as one of the best and cheap alternatives to PMMA to be used as the as the core material for high temperature condition due to its higher glass transition of 150 ℃ and high thermal stability. However, the fabrication of PC optical fibre parameter and material for the cladding material has not been well explored. Besides that, the sensitivity of the PC optical fibre sensor is relatively low. Thus this, study is focusing on the development of high thermal resistant PC optical fibre sensor with high sensitivity for the application in oil field.

A widely used technique to fabricate the PC POF is drill-and-draw technique. However, this technique is very difficult and consume a lot of time. Hence, a simpler technique is used in this study which is melt extrusion technique to fabricate the solid core. Nontheless, serious attention has to be paid in order to obtain a high quality of PC POF. In this technique, temperature control during the fabrications is very crucial as a non-suitable temperature may lead to a poor performance of POF. The processing temperature for fabrication of PC fibre optic is not well documented. The extrusion of POF require a precise extrusion temperature to avoid degradation of the polymer and unfavourable morphology. Therefore, the extrusion temperature for PC fibre optic in the range of 250 ℃ to 310 ℃ is studied. In this work, it is important to investigate the optimum temperature for the fabrication of the PC based POF. In addition to that, the diameter of the fibre also plays an important role. The measurement of using POF sensor yield a lower resolution due to its bigger diameter. Thus, the take up speed during the fabrication of POF will be studied to obtain the correct POF diameter to increase the accuracy during the measurement using POF sensor.

Cladding layer of PC POF also plays a crucial role. Application of PMMA as the cladding material for PC fibre is not sufficient due to its low thermal resistant, therefore blending of PMMA with a higher thermal resistant material is seen as one of the best options to increase its thermal properties. However, one of the main issues in PMMA and PC blending is its miscibility in which some study has been reported that blending of PMMA and PC would produce an opaque composite which is not favourable in fabrication of cladding layer (Yan *et al.*, 2021). Therefore, in this study the miscibility of those two polymers is investigated and the optimum ratio which give excellent optical and high thermal properties is determined. Other than that, polymethyl pentene (PMP) is also another potential candidate for fabrication of cladding layer. This polymer has high thermal resistant, but it has a slightly lower transparency than PMMA. Due to this, two types of cladding layer is prepared made from PC/PMMA blend and PMP polymer and the effect of different cladding layer on the light propagation on PC fibre core is investigated and the best cladding material is chosen.

Fibre Bragg grating (FBG) sensor has so much potential for commercialization in oil and gas industry due to its unique properties controllable sensitivities, compact size, non-destructive and make it very much suitable for in-situ measurement device. The deposition of metal oxide material on etched fibre may enhanced the sensitivity of the sensor. The removal of the cladding layer was very much depending on the immersion of the fibre in the solvent. Therefore, in this study the etching time is studied to obtain the optimum immersion time to remove as much as cladding possible followed by the deposition of the TiO_2 nanoparticles. In this study, TiO_2 was chosen due to its high refractive index properties as well as non-toxic, environmentally friendly and low cost. Although the use of PC POF Bragg grating sensor in oil flow detection for reservoir monitoring is relatively new, its potential is still alluring. Therefore, in this study the sensitivity of the sensor to perform in elevated temperature is determined by static test and the capability of the sensor to detect oil flow movement in high operating condition is conducted in dynamic test.

1.3 Objectives of Study

The main objective of this work is to produce a polymer optical fibre with an excellent quality to be used in harsh condition such as high pressure and high temperature condition. Then, this fibre is going to be incorporated with a sensor layer to study the oil propagation inside the porous media for reservoir monitoring. These aims are achieved through detailed fabrication process and measurement of wavelength shift due to oil movement in the porous media which conducted in the laboratory. The specific research objectives are as follows:

i. To examine the effect of temperature and collector speed on the optical, thermal, and mechanical properties of the PC core fibre.
ii. To investigate the optical and thermal properties of different cladding composition and its effect on the mechanical, morphology and optical performance of the PC fibre.
iii. To evaluate the sensitivity of the POF sensor to monitor water movement in the porous media at elevated temperature for reservoir monitoring.

1.4 Scope of Study

The following research activities are conducted in order to monitor the oil flow movement in the porous media. The scopes of study are outlined as follows:

For Objective 1:

a. The extrusion of the PC core fibre was conducted using single screw extruder and the temperature of the nozzle was set at 250 ℃, 270 ℃, 290 ℃, and 310 ℃.
b. The extrusion of PC POF core was performed at collector speed of 5 rpm, 10 rpm, 15 rpm and 20 rpm.
c. Characterizing the optical, mechanical, and thermal properties of the fabricated PC POF and the best extrusion temperature and collector speed was determined.

For Objective 2:

a. The PC/PMMA and PMP cladding were first casted into a flat sheet for characterisation of their optical and thermal properties.
b. The PC/PMMA flat sheet polymer ratio was varied from 100/0, 95/0, 85/0, 80/0, 75/0 and 70/0, subsequently the optimum ratio was determined.
c. The optimum ratio of PC/PMMA and PMP were used to fabricate the cladding layer on the PC core fibre via dip-coating method.
d. Characterizing the morphological, mechanical and optical properties of the prepared PC core with different cladding materials and the fibre was evaluated, subsequently the best combination was selected.

For Objective 3:

a. Prior to the deposition of TiO_2, the cladding layer was partially removed by chemical etching method and the etching time was varied from 5 min, 7 min, 9 min and 11 min, subsequently the optimum etching time was determined.
b. The sensitive sensor part was fabricated by deposition of metal oxide i.e titanium dioxide (TiO_2) onto the POF using the dip-coating technique and the surface roughness was evaluated.
c. Different refractive index fluid was prepared by mixing 20,000 ppm of saline water with different paraffin oil concentrations i.e 100/0, 25/75, 50/50, 75/25, 100/0.
d. The sensitivity of the sensor at elevated temperature of 60 °C, 90 °C and 120 °C was evaluated.
e. The ability of PC POF sensor to detect the oil movement inside the porous media was investigated and the experiment was conducted at operation temperature of 120 °C.

1.5 Significance of Study

Oil and gas industry has been facing a very tough and challenging situation for the past few years in which the oil prices have plunged from over \$ 100 USD per barrel to under \$ 35 USD per barrel in March 2020. Though currently the oil prices are getting better, yet still relatively low. Current announcements of discoveries are mostly marginal fields; therefore, oil companies are focusing on adding value and optimisation the existing assets. Thus, many companies are turning into big data and analytics to help weather the storm. Therefore, there is a need for more advanced monitoring device that can provide actionable data to increase production efficiency. The increased interest to use optical fibre sensor for data acquisition in such condition has become one of the drivers for many researchers to utilize this technology as it offers so many advantages over the other sensing technologies.

In this study, new and promising findings on the capability of the polymeric optical fibre sensor to detect oil movement inside the porous media are presented. A thorough analysis from this study has demonstrated an encouraging proof of concept, nonetheless more studies are needed before this technology can be used in real application. Combination of fibre Bragg grating sensor with evanescent field theories in PC optical fibre to detect the oil detection movement in porous media at high operating condition is very promising. Therefore, the outcomes of this study may be the basis of an extended study to be undertaken by other researchers in exploring the alternative to the outcomes for this study which may result in a better enhancement of technology. Besides that, the results gained in this work would also be very beneficial for oil companies to help in their efforts to optimise hydrocarbon production throughout the life of a field. Furthermore, this real time data acquisition technology has the potential to revolutionise the oil industries particularly in reservoir monitoring technique as this information obtained from this technology could contributes in term of its efficiency, safety and ultimate recovery.

1.6 Thesis Organisation

This thesis begins with **Chapter 1** which discusses on the research background and limitations that has led to this research. To complete this study, three objectives are registered and the scopes for this study are identified to complete all the objectives. The last section of this chapter is explaining about the implication of this work followed by summary of each chapter.

A comprehensive literature review is discussed in **Chapter 2**. It begins by describing few downhole monitoring techniques including the fibre optic sensor. Then, a more detailed discussion on fibre optic including its application, the core and cladding materials, fabrication technique and its properties. The last part of this chapter is focusing on reviewing the fibre optic sensor comprising the basic principle of fibre optic sensor, application of fibre optic sensors, Bragg grating sensor in polymer fibre, fabrication of Bragg grating and nanoparticles for coating on the sensing region to enhance its sensitivity.

In **Chapter 3**, the materials, methodologies, and the instruments used to complete this work are described attentively. In this chapter, a complete research framework is outlined. All the methods and parameters used to fabricate the PC fibre core, cladding and sensor region is mentioned in detail. This includes the description on the characterisation methods for the resultant fibre and fibre sensors. An experimental setup to evaluate the sensitivity of the PC fibre sensors and its ability to detect the oil movement in porous media at high temperature is also explained.

Chapter 4 presents the results of extrusion temperature and its effect on the optical and thermal properties of the PC core fibre. The effect of collector speed during the extrusion process on the structural and mechanical properties are also determined. In this chapter, the optimum extrusion temperature and collector speed for fabrication of PC core fibre is identified.

The best cladding materials for the PC core fibre is revealed in **Chapter 5**. In the first part of this chapter, the optical and thermal properties of PC/PMMA and PMP cladding layer are discussed and the optimum ratio for PC/PMMA is determined. In the second part, the optimum ratio of PC/PMMA and PMP cladded PC core fibre is compared in term of its mechanical, morphology and optical performance. The best cladding material for PC core is determined in the last part of this chapter.

Chapter 6 is focusing on the results of the sensing layer. In this chapter, the best etching time is determined. The properties and mechanism of deposited nanoparticles is also explained in this chapter. This chapter also reveals the sensitivity of the sensor at high operating conditions and its ability to perform as a sensor to detect the oil flow movement in porous media at high operating condition is presented.

Finally, few conclusions from this work are drawn and recommendation for future work are outlined in **Chapter 7**.

REFERENCES

Acakpovi, A. and Matoumona, P.L.M.V., 2012. Comparative analysis of plastic optical fiber and glass optical fiber for home networks. *2012 IEEE 4th International Conference on Adaptive Science & Technology (ICAST)*. October 2012 IEEE, pp. 154–157.

Addanki, S., Amiri, I.S. and Yupapin, P., 2018. Review of optical fibers-introduction and applications in fiber lasers. *Results in Physics*, 10(June), pp.743–750. Available at: https://doi.org/10.1016/j.rinp.2018.07.028.

Ahamed, S. V., 2013. Optical Fiber in Modern Networks. In: *Intelligent Networks*. Elsevier, pp. 93–106.

Ali, I. et al., 2018. Assessment of blend PVDF membranes, and the effect of polymer concentration and blend composition. *Membranes*, 8(1).

Ali, U., Karim, K.J.B.A. and Buang, N.A., 2015. A Review of the Properties and Applications of Poly (Methyl Methacrylate) (PMMA). *Polymer Reviews*, 55(4), pp.678–705.

An, N., Yang, Y. and Dong, L., 2007. Suppression of phase separation in PC/PMMA blend film by thermoset oligomer. *Macromolecules*, 40(2), pp.306–311.

Antunes, P., Domingues, F., Granada, M. and Andr, P., 2012. Mechanical Properties of Optical Fibers. In: *Selected Topics on Optical Fiber Technology*. InTech, pp. 1–15.

Aouachria, K. and Belhaneche-Bensemra, N., 2006. Miscibility of PVC/PMMA blends by vicat softening temperature, viscometry, DSC and FTIR analysis. *Polymer Testing*, 25(8), pp.1101–1108.

Arasu, P.T. et al., 2014. Absorbance properties of gold coated fiber Bragg grating sensor for aqueous ethanol. *Journal of the European Optical Society: Rapid Publications*, 9, p.14018.

Argyros, A., 2009. Structure, properties and characteristics of optical fibres. In: *Handbook of Textile Fibre Structure*. Elsevier, pp. 458–484.

Argyros, A., van Eijkelenborg, M.A., Large, M.C. and Bassett, I.M., 2006. Hollow-core microstructured polymer optical fiber. *Optics Letters*, 31(2), p.172.

Aris, A.M. et al., 2017. Tapered Fiber Bragg Grating Sensor Coated with Zinc Oxide Nanostructures for Humidity Measurement. *Journal of Telecommunication, Electronic and Computer Engineering (JTEC)*, 9(1–5), pp.1–5.

Arrospide, E. et al., 2017. Mechanical properties of polymer-optical fibres. In: *Polymer Optical Fibres*. Elsevier, pp. 201–216.

Azad, S., Parvizi, R. and Sadeghi, E., 2018. Tapered Optical Fiber Coated with ZnO Nanorods for Detection of Ethanol Concentration in Water. *International Journal of Optics and Photonics*, 12(2), pp.109–118.

Balani, K., Verma, V., Agarwal, A. and Narayan, R., 2015. Physical, Thermal, and Mechanical Properties of Polymers. In: *Biosurfaces*. John Wiley & Sons, Inc, Hoboken, NJ, USA, pp. 329–344.

Baldwin, C., 2018. Fiber Optic Sensors in the Oil and Gas Industry: Current and Future Applications. In: *Opto-Mechanical Fiber Optic Sensors*. Elsevier, pp. 211–236.

Baldwin, C., 2014. Optical fiber sensing in the oil and gas industry: overcoming challenges. *23rd International Conference on Optical Fibre Sensors*. 2 June 2014 Santander, Spain, pp. 9157C4-1-9157C4-4.

Bao, N. et al., 2010. Si-doped mesoporous TiO2 continuous fibers: Preparation by centrifugal spinning and photocatalytic properties. *Journal of Hazardous Materials*, 174(1–3), pp.129–136. Available at: https://linkinghub.elsevier.com/retrieve/pii/S0304389409014721.

Batocchio, M.A.P. et al., 2010. Case History – Steam Injection Monitoring with Optical–Fiber–Distributed Temperature Sensing. *All Days*. 23 March 2010 SPE, pp. 404–412.

Beckers, M. et al., 2015. An overview on fabrication methods for polymer optical fibers. *Polymer International*, 64(1), pp.25–36.

Beckers, M. et al., 2017. Fabrication techniques for polymer optical fibres. In: *Polymer Optical Fibres*. Elsevier, pp. 187–199.

Bera, S., Udayabhanu, G., Narayan, R. and Rout, T., 2016. Methodologies of Application of Sol-Gel Based Solution onto Substrate: A Review. *Journal of Coating Science and Technology*, 3(1), pp.9–22.

Berghmans, F. and Thienpont, H., 2014. Plastic Optical Fibers for Sensing Applications. *Optical Fiber Communication Conference*. 2014 OSA, Washington, D.C., p. Tu3K.2.

Berron, C. et al., 2015. Permanent, continuous & unmanned 4D seismic monitoring: Peace River case study. *SEG Technical Program Expanded Abstracts 2015*. 19 August 2015 Society of Exploration Geophysicists, pp. 5419–5423.

Bertolucci, P.R.H. et al., 1998. Radiation effects of low refractive index, fluorinated methacrylate polymers for fiber cladding. *Polymer Engineering & Science*, 38(4), pp.699–705.

Bhowmik, K. and Peng, G., 2019. *Handbook of Optical Fibers*,

Blaker, T. et al., 2002. Foam for Gas Mobility Control in the Snorre Field: The FAWAG Project. *SPE Reservoir Evaluation & Engineering*, 5(04), pp.317–323.

Bosc, D. and Toinen, C., 1993. Tensile mechanical properties and reduced internal stresses of polymer optical fiber. *Polymer Composites*, 14(5), pp.410–413.

Bostick, F.X., 2003. Commercialization of Fiber Optic Sensors for Reservoir Monitoring. *Offshore Technology Conference*. 8 April 2003 Offshore Technology Conference.

BP, 2020. Statistical Review of World Energy globally consistent data on world energy markets . and authoritative publications in the field of energy The Statistical Review world of World Energy and data on world energy markets from is The Review has been providing. , p.66.

British Petroleum, 2017. BP Statistical Review of World Energy 2017. *British Petroleum*, (66), pp.1–52.

Broadway, C., Kinet, D., et al., 2019. CYTOP fibre bragg grating sensors for harsh radiation environments. *Sensors (Switzerland)*, 19(13), pp.1–11.

Broadway, C. et al., 2015. Polymer optical fibre sensors for endoscopic optoacoustic imaging. *International Society for Optical Engineering*. 16 July 2015 p. 953907.

Broadway, C., Min, R., et al., 2019. Toward Commercial Polymer Fiber Bragg Grating Sensors: Review and Applications. *Journal of Lightwave Technology*, 37(11), pp.2605–2615.

Bubmann, T., Seidel, A. and Altstädt, V., 2019. Transparent PC/PMMA Blends Via Reactive Compatibilization in a Twin-Screw Extruder. *Polymers*, 11(12), p.2070. Available at: https://www.mdpi.com/2073-4360/11/12/2070.

Bundalo, I.-L., Nielsen, K., Markos, C. and Bang, O., 2014. Bragg grating writing in PMMA microstructured polymer optical fibers in less than 7 minutes. *Optics Express*, 22(5), pp.5270–5276.

Bunge, C.A., Beckers, M. and Gries, T., 2014. Simple and adjustable fabrication process for graded-index polymer optical fibers with tailored properties for sensing. *Proceedings of IEEE Sensors*, 2014-Decem(December), pp.1527–1530.

Butzbach, G.D. and Wendorff, J.H., 1991. Polycarbonate-poly(methyl methacrylate) blends: the role of molecular interactions on miscibility and antiplasticization. *Polymer*, 32(7), pp.1155–1159.

Campanella, C.E. et al., 2018. Fibre Bragg Grating based strain sensors: Review of technology and applications. *Sensors (Switzerland)*, 18(9).

Cerrahoglu, C., Naldrett, G., Vigrass, A. and Aghayev, R., 2019. Cluster flow identification during multi-rate testing using a wireline tractor conveyed distributed fiber optic sensing system with engineered fiber on a HPHT horizontal unconventional gas producer in the Liard basin. *Proceedings - SPE Annual Technical Conference and Exhibition*, 2019-Septe.

Chean, V., Robin, E., El Abdi, R. and Sangleboeuf, J.C., 2010. Study of the mechanical behavior of the optical fiber by a mark-tracking method. *EPJ Web of Conferences*, 6.

Cheng, F. et al., 2014. UV-stable paper coated with APTES-modified P25 TiO2 nanoparticles. *Carbohydrate Polymers*, 114, pp.246–252.

Cheng, X., Bonefacino, J., Guan, B.O. and Tam, H.Y., 2018. All-polymer fiber-optic pH sensor. *Optics Express*, 26(11), p.14610.

Chervanyov, A.I., 2018. Depletion interaction between colloids mediated by an athermal polymer blend. *Physical Review E*, 97(3), pp.1–10.

Choi, D. et al., 2004. Preparation and properties of methyl methacrylate and fluoroacrylate copolymers for plastic optical fiber cladding. *Journal of Applied Polymer Science*, 93(5), pp.2082–2089.

Coelho, L., Viegas, D., Santos, J.L.L. and De Almeida, J.M.M.M.M.M.M., 2016. Characterization of zinc oxide coated optical fiber long period gratings with improved refractive index sensing properties. *Sensors and Actuators B: Chemical*, 223, pp.45–51.

Collins, L., 2013. Optical Network Security. In: *Computer and Information Security Handbook*. Elsevier, pp. 363–370.

Constantinou, A. et al., 2016. Comparison of fibre optic sensor and Borehole Seismometer VSP surveys in a Scientific Borehole - DFDP-2B, Alpine Fault, New Zealand. *SEG Technical Program Expanded Abstracts*, 35, pp.5608–5612.

Cubillos, H., Torgersen, H.J., Chatzichristos, C. and Lamela Tobio, M., 2006. Best Practice and Case Study of Interwell Tracer Program Designs. *Proceedings of First International Oil Conference and Exhibition in Mexico*. August 2006 Society of Petroleum Engineers.

Cubillos, H., Torgersen, H.J., González, O. and Lamela Tobio, M., 2007. Application of Tracer Technology for Optimising RKF Miscible Gas Injection Recovery - Field Case. *SPE Europec/EAGE Annual Conference*. 4 April 2007 Society of Petroleum Engineers.

Culshaw, B., 2004. Optical Fiber Sensor Technologies: Opportunities and - Perhaps - Pitfalls. *Journal of Lightwave Technology*, 22(1), pp.39–50.

Curtis, C. et al., 2002. Heavy-oil reservoirs. *Oilfield Review*, 14, pp.30–51.

Cusano, A., Cutolo, A. and Giordano, M., 2008. Fiber Bragg Gratings Evanescent Wave Sensors: A View Back and Recent Advancements. In: *Sensors*. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 113–152.

Davies, E. et al., 2009. Sol-gel derived coating applied to long-period gratings for enhanced refractive index sensing properties. *Journal of Optics A: Pure and Applied Optics*, 11(1).

Dean, T. et al., 2015. Vertical seismic profiles: Now just another log? *SEG New Orleans Annual Meeting*. 19 August 2015 Society of Exploration Geophysicists, pp. 5544–5548.

Dehghani, M., Patel, R.B. and Singh, B.P., 2011. Applications of Fiber Optical Sensors in Petroleum Industry. *AIP Conference Proceedings*. 2011 pp. 36–38.

Delepine-Lesoille, S. et al., 2017. France's State of the Art Distributed Optical Fibre Sensors Qualified for the Monitoring of the French Underground Repository for High Level and Intermediate Level Long Lived Radioactive Wastes. *Sensors*, 17(6), p.1377.

Dezabala, E. et al., 2011. Application of Single Well Chemical Tracer Tests to Determine Remaining Oil Saturation in Deepwater Turbidite Reservoirs. *SPE Annual Technical Conference and Exhibition*. 4 April 2011 Society of Petroleum Engineers, pp. 1–13.

Dixit, M. et al., 2009. Morphology, miscibility and mechanical properties of PMMA/PC blends. *Phase Transitions*, 82(12), pp.866–878.

Djuraev, U., Jufar, S.R. and Vasant, P., 2017. A review on conceptual and practical oil and gas reservoir monitoring methods. *Journal of Petroleum Science and Engineering*, 152(August 2016), pp.586–601.

Dupuis, J.C., Butler, K.E., Kepic, A.W. and Harris, B.D., 2009. Anatomy of a seismoelectric conversion: Measurements and conceptual modeling in boreholes penetrating a sandy aquifer. *Journal of Geophysical Research*, 114(B10), p.B10306.

Dyrli, A.D. and Leung, E., 2017. Ten Years of Reservoir Monitoring with Chemical Inflow Tracers - What Have We Learnt and Applied Over the Past Decade? *SPE Kuwait Oil & Gas Show and Conference*. 15 October 2017 Society of Petroleum Engineers.

El-Naggar, A.M., Lopez, L.C. and Wilkes, G.L., 1990. Effect of electron beam radiation on the mechanical and thermal properties of poly(4-methylpentene-1). *Journal of Applied Polymer Science*, 39(2), pp.427–446.

Fasano, A. et al., 2016. Fabrication and characterization of polycarbonate microstructured polymer optical fibers for high-temperature-resistant fiber Bragg grating strain sensors. *Optical Materials Express*, 6(2), p.649.

Feng, Y. et al., 2014. Thermal degradation mechanism and kinetics of polycarbonate/silica nanocomposites. *Polymer Degradation and Stability*, 107, pp.129–138.

Fernandes, D. et al., 2017. Influence of temperature on the refractive index sensitivities of fiber bragg gratings refractometers. *Journal of Microwaves, Optoelectronics and Electromagnetic Applications*, 16(2), pp.385–392.

Fidanboylu, K. and Efendioglu, H.S., 2009. FIBER OPTIC SENSORS AND THEIR APPLICATIONS. *5th International Advanced Technologies Symposium (IATS’09)*. May 2009 Karabuk, Turkey, pp. 1–6.

Fidaner, O., 2017. Downhole Multiphase Flow Monitoring Using Fiber Optics. *SPE Annual Technical Conference and Exhibition*. 9 October 2017 Society of Petroleum Engineers, pp. 9–11.

Gad, M.M. et al., 2020. Influence of Addition of Different Nanoparticles on the Surface Properties of Poly(methylmethacrylate) Denture Base Material. *Journal of Prosthodontics*, 29(5), pp.422–428.

Gaidau, C. et al., 2017. Preparation of silica doped titania nanoparticles with thermal stability and photocatalytic properties and their application for leather surface functionalization. *Arabian Journal of Chemistry*, 10(7), pp.985–1000.

Gallego, D. and Lamela, H., 2017. Microstructured polymer optical fiber sensors for optoacoustic endoscopy. *Photons Plus Ultrasound: Imaging and Sensing 2017*. 22 March 2017 p. 1006412.

Gribaev, A.I. et al., 2016. Laboratory setup for fiber Bragg gratings inscription based on Talbot interferometer. *Optical and Quantum Electronics*, 48(12), pp.1–7.

Hamdalla, T.A. and Nafee, S.S., 2015. Bragg wavelength shift for irradiated polymer fiber Bragg grating. *Optics & Laser Technology*, 74, pp.167–172.

Harmon, J.P., 2001. Polymers for Optical Fibers and Waveguides: An Overview. In: *Optical Polymers*. pp. 1–23.

Hernaez, M. et al., 2010. Lossy mode resonances supported by TiO2-coated optical fibers. *Procedia Engineering*, 5, pp.1099–1102.

Hernandez, C. et al., 2002. Monitoring WAG Pilot at VLE Field, Maracaibo Lake, by Perfluorocarbon and Fluorined Benzoic Acids Tracers. *Proceedings of SPE/DOE Improved Oil Recovery Symposium*. April 2002 Society of Petroleum Engineers.

Hiscocks, M.P., van Eijkelenborg, M.A., Argyros, A. and Large, M.C.J., 2006. Stable imprinting of long-period gratings in microstructured polymer optical fibre. *Optics Express*, 14(11), p.4644.

Hisham, H.K., 2017. Bandwidth Characteristics of FBG Sensors for Oil and Gas Applications. , 4(1), pp.30–34.

Hisham, H.K., 2018. Optical Fiber Sensing Technology : Basics , Classifications and Applications. *American Journal of Remote Sensing*, 6(1), pp.1–5.

van der Horst, J. et al., 2014. Fibre Optic Sensing For Improved Wellbore Production Surveillance. *International Petroleum Technology Conference*. 19 January 2014 International Petroleum Technology Conference, pp. 1–7.

Hu, X. et al., 2014. Highly reflective Bragg gratings in slightly etched step-index polymer optical fiber. *Optics Express*, 22(15), p.18807.

Huang, X.F. et al., 2008. Design and characteristics of refractive index sensor based on thinned and microstructure fiber Bragg grating. *Applied Optics*, 47(4), pp.504–511.

Hubans, C., Cauquil, E.C. and Brechet, E., 2014. 4D (Time Lapse) Seismic: an Emerging Tool for Underwater Monitoring? *Offshore Technology Conference*. 5 May 2014 Offshore Technology Conference, pp. 5–8.

Humbert, G. et al., 2004. Hollow core photonic crystal fibers for beam delivery. *Optics Express*, 12(8), p.1477.

Ioannou, A., Theodosiou, A., Caucheteur, C. and Kalli, K., 2017. Direct writing of plane-by-plane tilted fiber Bragg gratings using a femtosecond laser. *Optics Letters*, 42(24), p.5198.

Ishigure, T., Aruga, Y. and Koike, Y., 2007. High-Bandwidth PVDF-Clad GI POF With Ultra-Low Bending Loss. *Journal of Lightwave Technology*, 25(1), pp.335–345.

Ishigure, T., Hirai, M., Sato, M. and Koike, Y., 2004. Graded-index plastic optical fiber with high mechanical properties enabling easy network installations. II. *Journal of Applied Polymer Science*, 91(1), pp.404–409.

Jaafar, M.Z., Ahmed, T., Sulaiman, W.R.W. and Ismail, A.R., 2015. Reservoir Monitoring Using Streaming Potential; Is the Thermoelectric Correction Necessary? *SPE Reservoir Characterisation and Simulation Conference and Exhibition*. 14 September 2015 Society of Petroleum Engineers.

Jaafar, M.Z., Omar, S., Anuar, S.M.M. and Suradi, S.R., 2014. Reservoir Monitoring of EOR Processes (WAG , Foam and Polymer) Using Streaming Potential. , (August), pp.231–238.

Jacobs, T., 2014. Downhole Fiber-Optic Monitoring: An Evolving Technology. *Journal of Petroleum Technology*, 66(08), pp.44–53.

Janting, J. et al., 2019. Effects of Solvent Etching on PMMA Microstructured Optical Fiber Bragg Grating. *Journal of Lightwave Technology*, 37(18), pp.4469–4479.

Javaheri, M. et al., 2020. Flow Profiling Using Fiber Optics in a Horizontal Steam Injector with Liner-Deployed Flow Control Devices. *SPE Journal*, (May), pp.1–15.

Jiang, C. et al., 2002. Fabrication and mechanical behavior of dye-doped polymer optical fiber. *Journal of Applied Physics*, 92(1), pp.4–12.

Jiang, P., Fan, Y. Van and Klemeš, J.J., 2021. Impacts of COVID-19 on energy demand and consumption: Challenges, lessons and emerging opportunities. *Applied Energy*, 285(January).

Jin, Y. and M Granville, A., 2016. Polymer Fiber Optic Sensors – A Mini Review of their Synthesis and Applications. *Journal of Biosensors & Bioelectronics*, 07(01), pp.1–11.

Johns, K. and Stead, G., 2000. Fluoroproducts - The extremophiles. *Journal of Fluorine Chemistry*, 104(1), pp.5–18.

Kausar, A., 2018. A review of filled and pristine polycarbonate blends and their applications. *Journal of Plastic Film & Sheeting*, 34(1), pp.60–97.

Khalaf, A.L. et al., 2017. Modified plastic optical fiber with CNT and graphene oxide nanostructured coatings for ethanol liquid sensing. *Optics Express*, 25(5), p.5509.

Khanarian, G., 2001. Optical properties of cyclic olefin copolymers. *Optical Engineering*, 40(6), p.1024.

Kim, J.-S., Kang, J.-W. and Kim, J.-J., 2003. Simple and Low Cost Fabrication of Thermally Stable Polymeric Multimode Waveguides using a UV-curable Epoxy. *Japanese Journal of Applied Physics*, 42(Part 1, No. 3), pp.1277–1279.

Koerdt, M. et al., 2014. Fabrication and Characterization of Bragg Gratings in a Graded-index Perfluorinated Polymer Optical Fiber. *Procedia Technology*, 15, pp.138–146.

Koerdt, M. et al., 2016. Fabrication and characterization of Bragg gratings in perfluorinated polymer optical fibers and their embedding in composites. *Mechatronics*, 34, pp.137–146.

Koike, K. and Koike, Y., 2009. Design of Low-Loss Graded-Index Plastic Optical Fiber Based on Partially Fluorinated Methacrylate Polymer. *Journal of Lightwave Technology*, 27(1), pp.41–46.

Koike, K., Suzuki, A., Makino, K. and Koike, Y., 2015. Effects of para-fluorine substituent of polystyrene on gradient-index fiber-optic properties. *Optical Materials*, 39, pp.143–147.

Koike, Y. and Gaudino, R., 2013. *Plastic Optical Fibers and Gb/s Data Links* Sixth Edit., Elsevier Inc.

Korposh, S. et al., 2012. Optical fibre long period grating with a nanoporous coating formed from silica nanoparticles for ammonia sensing in water. *Materials Chemistry and Physics*, 133(2–3), pp.784–792.

Korposh, S., Lee, S., James, S.W. and Tatam, R.P., 2011. Refractive index sensitivity of fibre-optic long period gratings coated with SiO 2 nanoparticle mesoporous thin films. *Measurement Science and Technology*, 22(7), p.075208.

Kragas, T. et al., 2002. Downhole Fiber-Optic Multiphase Flowmeter: Design, Operating Principle, and Testing. *Proceedings of SPE Annual Technical Conference and Exhibition*. September 2002 Society of Petroleum Engineers.

Kragas, T.K. et al., 2003. Downhole Fiber-Optic Flowmeter: Design, Operating Principle, Testing, and Field Installations. *SPE Production & Facilities*, 18(04), pp.257–268.

Kragas, T.K., Williams, B.A. and Myers, G.A., 2001. The Optic Oil Field: Deployment and Application of Permanent In-well Fiber Optic Sensing Systems for Production and Reservoir Monitoring. *SPE Annual Technical Conference and Exhibition*. 4 April 2001 Society of Petroleum Engineers, p. 9.

Kröplin, P. et al., 2017. Overview of the POF market. In: *Polymer Optical Fibres*. Elsevier, pp. 349–400.

Kuhne, J.F., de Oliveira, V., Kalinowski, H.J. and Canute Kamikawachi, R., 2015. Refractive index sensitivity of fiber Bragg grating inscribed in a multimode fiber. *2015 SBMO/IEEE MTT-S International Microwave and Optoelectronics Conference (IMOC)*. November 2015 IEEE, pp. 1–3.

Kumudinie, C., 2001. Polymer–Ceramic Nanocomposites: Interfacial Bonding Agents. In: *Encyclopedia of Materials: Science and Technology*. Elsevier, pp. 7574–7577.

Lacraz, A.A. et al., 2015. Femtosecond Laser Inscribed Bragg Gratings in Low Loss CYTOP Polymer Optical Fiber. *IEEE Photonics Technology Letters*, 27(7), pp.693–696.

Lanier, G.H., Brown, G. and Adams, L., 2003. Brunei Field Trial of a Fibre Optic Distributed Temperature Sensor (DTS) System in a 1,000m Open Hole Horizontal Oil Producer. *Proceedings - SPE Annual Technical Conference and Exhibition*, pp.2387–2392.

Lee, B., 2003. Review of the present status of optical fiber sensors. *Optical Fiber Technology*, 9(2), pp.57–79.

Li, Y. and Shimizu, H., 2011. Fabrication of nanostructured polycarbonate/poly(methyl methacrylate) blends with improved optical and mechanical properties by high-shear processing. *Polymer Engineering & Science*, 51(7), pp.1437–1445.

Li, Z., Tam, H.Y., Xu, L. and Zhang, Q., 2005. Fabrication of long-period gratings in poly(methyl methacrylate-co-methyl vinyl ketone-co-benzyl methacrylate)-core polymer optical fiber by use of a mercury lamp. *Optics Letters*, 30(10), p.1117.

Liu, Z. et al., 2014. Refractive index sensing characterization of a singlemode–claddingless–singlemode fiber structure based fiber ring cavity laser. *Optics Express*, 22(5), p.5037.

Luo, Y. et al., 2017. Fabrication of Polymer Optical Fibre (POF) Gratings. *Sensors*, 17(3), p.511.

Luo, Y. et al., 2007. Optical manipulable polymer optical fiber Bragg gratings with azopolymer as core material. *Applied Physics Letters*, 91(7), pp.2005–2008.

Maas, S. et al., 2004. Fiber optic 4C seabed cable field trials. *SEG Technical Program Expanded Abstracts 2004*. January 2004 Society of Exploration Geophysicists, pp. 925–928.

Machavaram, V.R., Badcock, R.A. and Fernando, G.F., 2007. Fabrication of intrinsic fibre Fabry-Perot sensors in silica fibres using hydrofluoric acid etching. *Sensors and Actuators, A: Physical*, 138(1), pp.248–260.

Majoul, N., Aouida, S. and Bessaïs, B., 2015. Progress of porous silicon APTES-functionalization by FTIR investigations. *Applied Surface Science*, 331, pp.388–391.

Maniruzzaman, M., Boateng, J.S., Snowden, M.J. and Douroumis, D., 2012. A Review of Hot-Melt Extrusion: Process Technology to Pharmaceutical Products. *ISRN Pharmaceutics*, 2012, pp.1–9.

Markos, C. et al., 2013. High-Tg TOPAS microstructured polymer optical fiber for fiber Bragg grating strain sensing at 110 degrees. *Optics Express*, 21(4), p.4758.

Marques, C.A.F. et al., 2018. Fast and stable gratings inscription in POFs made of different materials with pulsed 248 nm KrF laser. *Optics Express*, 26(2), p.2013.

Marques, C.A.F., Peng, G.-D. and Webb, D.J., 2015. Highly sensitive liquid level monitoring system utilizing polymer fiber Bragg gratings. *Optics Express*, 23(5), p.6058.

Martinez, A., Dubov, M., Khrushchev, I. and Bennion, I., 2004. Direct writing of fibre Bragg gratings by femtosecond laser. *Electronics Letters*, 40(19), p.1170.

Martinez, A., Khrushchev, I.Y. and Bennion, I., 2006. Direct inscription of Bragg gratings in coated fibers by an infrared femtosecond laser. *Optics Letters*, 31(11), p.1603.

McKeen, L.W., 2019. Polyolefins. In: *The Effect of UV Light and Weather on Plastics and Elastomers*. Elsevier, pp. 223–249.

Medina, M. et al., 2013. Real-time downhole monitoring of electrical submersible pumps rated to 250°C using fiber optic sensors: Case study and data value in the leismer SAGD project. *Society of Petroleum Engineers - 2013 SPE Artificial Lift Conference - Americas: Artificial Lift: Where Do We Go From Here*, pp.1–11.

Méndez, A., 2016. Optics in Medicine. In: Al-Amri, M.D., El-Gomati, M. and Zubairy, M.S., (eds.) *Optics in Our Time*. Springer International Publishing, Cham, pp. 299–333.

Meroni, D. et al., 2017. A close look at the structure of the TiO2-APTES interface in hybrid nanomaterials and its degradation pathway: An experimental and theoretical study. *Journal of Physical Chemistry C*, 121(1), pp.430–440.

Min, R. et al., 2018. Bragg gratings inscription in TS-doped PMMA POF by using 248-nm KrF pulses. *IEEE Photonics Technology Letters*, 30(18), pp.1609–1612.

Min, R., Ortega, B. and Marques, C., 2019. Latest Achievements in Polymer Optical Fiber Gratings: Fabrication and Applications. *Photonics*, 6(2), p.36.

Mohammed, P.A., 2021. Integration of self-standing X- and Y- shaped polymer coupler and splitter with single mode optical fibers. *Optical Materials*, 111(September 2020), p.110685.

Montaudo, G., Puglisi, C. and Samperi, F., 1998. Chemical reactions occurring in the thermal treatment of PC/PMMA blends. *Journal of Polymer Science Part A: Polymer Chemistry*, 36(11), pp.1873–1884.

Morova, B. et al., 2019. Fabrication and characterization of large numerical aperture, high-resolution optical fiber bundles based on high-contrast pairs of soft glasses for fluorescence imaging. *Optics Express*, 27(7), p.9502.

Muggeridge, A. et al., 2013. Recovery rates, enhanced oil recovery and technological limits. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 372(2006), pp.20120320–20120320.

Murugesan, S. et al., 2017. Multicolor Fluorescent Silica Nanoparticles as Tracers for Production and Well Monitoring. *SPE Annual Technical Conference and Exhibition*. 9 October 2017 Society of Petroleum Engineers.

Muto, S., Suzuki, O., Amano, T. and Morisawa, M., 2003. A plastic optical fibre sensor for real-time humidity monitoring. *Measurement Science and Technology*, 14(6), pp.746–750.

Nacci, A., Ursino, F., La Vela, R., Matteucci, F., Mallardi, V., & Fattori, B. (2008). Fiberoptic endoscopic evaluation of swallowing (FEES): proposal for informed consent. *Acta otorhinolaryngologica Italica : organo ufficiale della Societa italiana di otorinolaringologia e chirurgia cervico-facciale*, 28(4), 206–211.

Nakao, R., Kondo, A. and Koike, Y., 2012. Fabrication of High Glass Transition Temperature Graded-Index Plastic Optical Fiber: Part 2—Fiber Fabrication and Characterizations. *Journal of Lightwave Technology*, 30(7), pp.969–973.

Nematollahi, M.H., Dehaghani, A.H.S. and Abedini, R., 2016. CO2/CH4 separation with poly(4-methyl-1-pentyne) (TPX) based mixed matrix membrane filled with Al2O3 nanoparticles. *Korean Journal of Chemical Engineering*, 33(2), pp.657–665.

Omar, S., Jaafar, M.Z., Ismail, A.R. and Wan Sulaiman, W.R., 2013. Monitoring Foam Stability in Foam Assisted Water Alternate Gas (FAWAG) Processes Using Electrokinetic Signals. *SPE Enhanced Oil Recovery Conference*. 2 July 2013 Society of Petroleum Engineers.

Orangi, A. and Ershaghi, I., 2008. Flood Front Tracking and Pulse Test Time Lags. *SPE Symposium on Improved Oil Recovery*. 4 April 2008 Society of Petroleum Engineers, pp. 19–23.

Paliwal, N. and John, J., 2014. Sensitivity Enhancement of Aluminium Doped Zinc Oxide (AZO) Coated Lossy Mode Resonance (LMR) Fiber Optic Sensors Using Additional Layer of Oxides. *Frontiers in Optics 2014*. 2014 OSA, Washington, D.C., p. JTu3A.40.

Park, S.-J., Cho, K.-S. and Choi, C.-G., 2003. Effect of fluorine plasma treatment on PMMA and their application to passive optical waveguides. *Journal of Colloid and Interface Science*, 258(2), pp.424–426.

Peng, G.-D. and Chu, P.L., 2002. Polymer Optical Fibre Sensing. *Optical Information Processing Technology*, 4929(2002), pp.303–311.

Perlicki, K. and Wilczewski, G., 2015. Fiber optics transmission for vehicle applications. *Measurement Automation Monitoring*, 61(03), pp.81–83.

Peters, K., 2011. Polymer optical fiber sensors—a review. *Smart Materials and Structures*, 20(1), p.013002.

Pimbert, S., Avignon-Poquillon, L. and Levesque, G., 2001. Fluorinated Polymer Blends as Plastic Optical Fibers Cladding Materials. In: *Optical Polymers: Fibers and Waveguides*. pp. 113–128.

Pjević, D. et al., 2015. Properties of sputtered TiO2 thin films as a function of deposition and annealing parameters. *Physica B: Condensed Matter*, 463, pp.20–25.

Plümpe, M. et al., 2017. Applications of polymer-optical fibres in sensor technology, lighting and further applications. In: *Polymer Optical Fibres*. Elsevier, pp. 311–335.

Polishuk, P., 2006. Plastic optical fibers branch out. *IEEE Communications Magazine*, 44(9), pp.140–148.

Poomalai, P., Ramaraj, B. and Siddaramaiah, 2007. Thermal and mechanical properties of poly(methyl methacrylate) and ethylene vinyl acetate copolymer blends. *Journal of Applied Polymer Science*, 106(1), pp.684–691.

Poomalai, P., Varghese, T.O. and Siddaramaiah, 2011. Thermomechanical Behaviour of Poly(methyl methacrylate)/Copoly(ether-ester) Blends. *ISRN Materials Science*, 2011, pp.1–5.

Prado, A.R. et al., 2017. Polymethyl methacrylate (PMMA) recycling for the production of optical fiber sensor systems. *Optics Express*, 25(24), p.30051.

Qazi, H.H. et al., 2019. Surface roughness and the sensitivity of D-shaped optical fibre sensors. *Journal of Modern Optics*, 66(11), pp.1244–1251.

Qiao, X., Shao, Z., Bao, W. and Rong, Q., 2017. Fiber Bragg Grating Sensors for the Oil Industry. *Sensors*, 17(3), p.429.

Rajh, T. et al., 2014. Titanium Dioxide in the Service of the Biomedical Revolution. *Chemical Reviews*, 114(19), pp.10177–10216.

Ramaswami, R., Sivarajan, K.N. and Sasaki, G.H., 2010. Propagation of Signals in Optical Fiber. In: *Optical Networks*. Elsevier, pp. 47–112.

Razak, W.N.A.W., Safuan Awg Sapawi, A.M., Zainal Abdullah, Z. and Abd Raub, M.R., 2019. Evaluation of reservoir cooling effect on IWAG performance for mature waterflooded Malaysian oil field. *SPE Middle East Oil and Gas Show and Conference, MEOS, Proceedings*, 2019-March.

Renganathan, B. et al., 2010. Nanocrystalline Titanium dioxide coated optical fiber sensor for ammonia vapour detection. 19 August 2010 p. 77640U.

Rioux, M. et al., 2017. Optical and electrical characterizations of multifunctional silver phosphate glass and polymer-based optical fibers. *Scientific Reports*, 7(1), p.43917.

Sadiku, R. et al., 2017. Automotive components composed of polyolefins. In: *Polyolefin Fibres*. Elsevier, pp. 449–496.

Sahota, J.K., Gupta, N. and Dhawan, D., 2020. Fiber Bragg grating sensors for monitoring of physical parameters: a comprehensive review. *Optical Engineering*, 59(06), p.1.

Samavati, Z., Samavati, A., Ismail, Ahmad Fauzi, et al., 2019. Comprehensive investigation of evanescent wave optical fiber refractive index sensor coated with ZnO nanoparticles. *Optical Fiber Technology*, 52(July), p.101976.

Samavati, Z., Samavati, A., Ismail, A. F., et al., 2019. Detection of saline-based refractive index changes via bilayer ZnO/Ag-coated glass optical fiber sensor. *Applied Physics B*, 125(9), p.161.

Sanchez, P. et al., 2014. Optical fiber refractometers based on Lossy Mode Resonances by means of SnO2 sputtered coatings. *Sensors and Actuators, B: Chemical*, 202, pp.154–159.

Sanchez, P. et al., 2016. Wind turbines lubricant gearbox degradation detection by means of a lossy mode resonance based optical fiber refractometer. *Microsystem Technologies*, 22(7), pp.1619–1625.

Sánchez, P. et al., 2012. SnO2 Based Optical Fiber Refractometers P. *OFS2012 22nd International Conference on Optical Fiber Sensors*. 17 October 2012 pp. 84216B-84216B–4.

Sato, M., Hirai, M., Ishigure, T. and Koike, Y., 2000. High temperature resistant graded-index polymer optical fiber. *Journal of Lightwave Technology*, 18(12), pp.2139–2145.

Saunders, J.H., Jackson, M.D. and Pain, C.C., 2008. Fluid flow monitoring in oil fields using downhole measurements of electrokinetic potential. *Geophysics*, 73(5), pp.E165–E180.

Seong, D.-W.W., Yeo, J.-S.S. and Hwang, S.-H.H., 2016. Fabrication of polycarbonate blends with poly(methyl methacrylate-co-phenyl methacrylate) copolymer: Miscibility and scratch resistance properties. *Journal of Industrial and Engineering Chemistry*, 36, pp.251–254.

Shakeri, A. et al., 2018. Self-cleaning ceramic tiles produced via stable coating of TiO2 Nanoparticles. *Materials*, 11(6).

Shanaghi, A., Rouhaghdam, A.S., Shahrabi, T. and Aliofkhazraei, M., 2008. Study of TiO2 nanoparticle coatings by the sol-gel method for corrosion protection. *Materials Science*, 44(2), pp.233–247.

Shao, M. et al., 2015. Refractive index measurement based on fiber Bragg grating connected with a multimode fiber core. *Optics Communications*, 351, pp.70–74.

Shen, W. et al., 2018. Endoscopic third ventriculostomy in children with a fiber optic neuroendoscopy. *Child's Nervous System*, 34(5), pp.837–844.

Singh, N., Jain, S.C., Aggarwal, A.K. and Bajpai, R.P., 2005. Fibre Bragg grating writing using phase mask technology. *Journal of Scientific and Industrial Research*, 64(2), pp.108–115.

Singh, Y., Sadhu, A. and Raghuwanshi, S.K., 2020. Development and Experimental Analysis of Titanium Dioxide (TiO 2) Coated Etched Fiber Bragg Grating Sensor for Chemical Sensing. *IEEE Sensors Journal*, 20(15), pp.8528–8534.

Skutnik, B.J. and Park, H., 2002. Cladding effects on spectral transmission of optical fibers for medical applications. *Optical Fibers and Sensors for Medical Applications II*. 27 March 2002 pp. 180–186.

Sridevi., S. et al., 2016. Ultra sensitive NO2 gas detection using the reduced graphene oxide coated etched fiber Bragg gratings. *Sensors and Actuators, B: Chemical*, 223(2), pp.481–486.

Stajanca, P. et al., 2017. Impacts of gamma irradiation on Cytop plastic optical fibres. *POF 2016 - 25th International Conference on Plastic Optical Fibres, Conference Proceedings*, (1), pp.114–117.

Stefani, A., Andresen, S., et al., 2012. High sensitivity polymer optical fiber-bragg-grating-based accelerometer. *IEEE Photonics Technology Letters*, 24(9), pp.763–765.

Stefani, A., Stecher, M., Town, G.E. and Bang, O., 2012. Direct Writing of Fiber Bragg Grating in Microstructured Polymer Optical Fiber. *IEEE Photonics Technology Letters*, 24(13), pp.1148–1150.

Sun, M. et al., 2012. Thermal formation of silicon-doped TiO2 thin films with enhanced visible light photoelectrochemical response. *Electrochemistry Communications*, 16(1), pp.26–29.

Suri, G., Jha, G.S., Seshadri, G. and Khandal, R.K., 2009. Modification of low refractive index polycarbonate for high refractive index applications. *International Journal of Polymer Science*, 2009(c).

Tahhan, S.R. et al., 2017. Fabrication of Fiber Bragg Grating Coating with TiO 2 Nanostructured Metal Oxide for Refractive Index Sensor. *Journal of Nanotechnology*, 2017, pp.1–9.

Takahashi, A., Inoue, A., Sassa, T. and Koike, Y., 2013. Fluorination effects on attenuation spectra of plastic optical fiber core materials. *Optical Materials Express*, 3(5), pp.233–236.

Takezawa, Y. et al., 1994. Low excess losses in a Y-branching plastic optical waveguide formed through injection molding. *Applied Optics*, 33(12), p.2307.

Tekelioglu, M. and Wood, B.D., 2005. Prediction of light-transmission losses in plastic optical fibers. *Applied Optics*, 44(12), p.2318.

Teng, H., 2012. Overview of the Development of the Fluoropolymer Industry. *Applied Sciences*, 2(4), pp.496–512.

Theodosiou, A. et al., 2016. Comparative study of multimode CYTOP graded index and single-mode silica fibre Bragg grating array for the mode shape capturing of a free-free metal beam. *Micro-Structured and Specialty Optical Fibres IV*. 27 April 2016 p. 98860O.

Theodosiou, A. et al., 2017. Plane-by-Plane Femtosecond Laser Inscription Method for Single-Peak Bragg Gratings in Multimode CYTOP Polymer Optical Fiber. *Journal of Lightwave Technology*, 35(24), pp.5404–5410.

Theodosiou, A., Komodromos, M. and Kalli, K., 2018. Carbon Cantilever Beam Health Inspection Using a Polymer Fiber Bragg Grating Array. *Journal of Lightwave Technology*, 36(4), pp.986–992.

Thorat, P. V, Warulkar, S. and Thombre, P.A., 2014. Plastic optical fiber. *International Journal of Engineering Research and Reviews*, 2(4), pp.95–105.

Tiwari, S.K. et al., 2017. Mixing sequence driven controlled dispersion of graphene oxide in PC/PMMA blend nanocomposite and its effect on thermo-mechanical properties. *Current Applied Physics*, 17(9), pp.1158–1168.

Tork, A. et al., 2001. Photochromic behavior of spiropyran in polymer matrices. *Applied Optics*, 40(8), p.1180.

Turner, A. and Loustau, P., 2015. Fiber Optic Sensor Based Monitoring System for Blowout Preventer. *Offshore Technology Conference*. 4 May 2015 Offshore Technology Conference, pp. 4–7.

Uyor, U.O., Popoola, A.P.I., Popoola, O.M. and Aigbodion, V.S., 2019. Polymeric cladding materials under high temperature from optical fibre perspective: a review. *Polymer Bulletin*, 77(4), pp.2155–2177.

Vicente, A. et al., 2019. Lossy mode resonance sensors based on nanocoated multimode-coreless-multimode fibre. *Sensors and Actuators, B: Chemical*, 304(April 2019), p.126955.

Viegas, D. et al., 2009. A fibre optic humidity sensor based on a long-period fibre grating coated with a thin film of SiO 2 nanospheres. *Measurement Science and Technology*, 20(3), p.034002.

Del Villar, I. et al., 2010. Lossy Mode Resonance Generation With Indium-Tin-Oxide-Coated Optical Fibers for Sensing Applications. *Journal of Lightwave Technology*, 28(1), pp.111–117.

Wanag, A. et al., 2020. Influence of modification of titanium dioxide by silane coupling agents on the photocatalytic activity and stability. *Journal of Environmental Chemical Engineering*, 8(4), p.103917.

Wang, Q. and Zhao, W.M., 2018. A comprehensive review of lossy mode resonance-based fiber optic sensors. *Optics and Lasers in Engineering*, 100(July 2017), pp.47–60.

Webb, D.J., 2015. Fibre Bragg grating sensors in polymer optical fibres. *Measurement Science and Technology*, 26(9), p.092004.

Woyessa, G., Fasano, A., Markos, C., Rasmussen, H.K., et al., 2017. Low Loss Polycarbonate Polymer Optical Fiber for High Temperature FBG Humidity Sensing. *IEEE Photonics Technology Letters*, 29(7), pp.575–578.

Woyessa, G., Fasano, A., et al., 2016. Single mode step-index polymer optical fiber for humidity insensitive high temperature fiber Bragg grating sensors. *Optics Express*, 24(2), p.1253.

Woyessa, G., Nielsen, K., et al., 2016. Temperature insensitive hysteresis free highly sensitive polymer optical fiber Bragg grating humidity sensor. *Optics Express*, 24(2), p.1206.

Woyessa, G., Fasano, A., Markos, C., Stefani, A., et al., 2017. Zeonex microstructured polymer optical fiber: fabrication friendly fibers for high temperature and humidity insensitive Bragg grating sensing. *Optical Materials Express*, 7(1), p.286.

Xia, Q. et al., 2014. The Morphological properties of SnCl2·2H2O-modified PC/PMMA blends. *Iranian Polymer Journal*, 23(12), pp.955–964.

Xia, Q.Y., Ying, S.J. and Luo, Y.X., 2014. Solvent cast blends of PMMA microspheres in bisphenol-A-polycarbonate. *Plastics, Rubber and Composites*, 43(9), pp.284–289.

Xiong, Z., Peng, G.D., Wu, B. and Chu, P.L., 1999. Highly Tunable Bragg Gratings in Single-Mode Polymer Optical Fibers. *IEEE Photonics Technology Letters*, 11(3), pp.352–354.

Yamashita, T. and Kamada, K., 1993. Intrinsic Transmission Loss of Polycarbonate Core Optical Fiber. *Japanese Journal of Applied Physics*, 32(Part 1, No. 6A), pp.2681–2686.

Yamate, T., 2008. Fiber optic sensors for the exploration of oil and gas. *Proc. SPIE*. 14 April 2008 p. 700438.

Yan, T., Xu, H. and Li, Y., 2021. Crosslinked network formation beyond graft copolymers in transparent bisphenol-A Polycarbonate/Poly(methyl methacrylate) blends catalyzed by bis(trifluoromethanesulphonyl)imide based organic salts. *Polymer*, 223(March), p.123700.

Yan, Y. et al., 2018. A new method for calculating the primary porosity of unconsolidated sands based on packing texture: Application to modern beach sand. *Marine and Petroleum Geology*, 98(August), pp.384–396.

Yang, D.., Yu, J., Tao, X. and Tam, H., 2004. Structural and mechanical properties of polymeric optical fiber. *Materials Science and Engineering: A*, 364(1–2), pp.256–259.

Yoshida, H. et al., 2014. Effect of cladding layer glass transition temperature on thermal resistance of graded-index plastic optical fibers. *Polymer Journal*, 46(11), pp.823–826.

Yu, J., Tao, X. and Tam, H., 2006. Fabrication of UV sensitive single-mode polymeric optical fiber. *Optical Materials*, 28(3), pp.181–188.

Yu, Y. et al., 2020. High-precision fiber Bragg gratings inscription by infrared femtosecond laser direct-writing method assisted with image recognition. *Optics Express*, 28(6), p.8937.

Yuan, W. et al., 2011. Humidity insensitive TOPAS polymer fiber Bragg grating sensor. *Optics Express*, 19(20), p.19731.

Zamarreno, C.R., Sanchez, P., et al., 2010. Dual-peak resonance-based optical fiber refractometers. *IEEE Photonics Technology Letters*, 22(24), pp.1778–1780.

Zamarreno, C.R., Hernaez, M., et al., 2010. ITO Coated Optical Fiber Refractometers Based on Resonances in the Infrared Region. *IEEE Sensors Journal*, 10(2), pp.365–366.

Zamarreno, C.R. et al., 2012. Sensing properties of indium oxide coated optical fiber devices based on lossy mode resonances. *IEEE Sensors Journal*, 12(1), pp.151–155.

Zaremba, D. and Evert, R., 2017. Materials, chemical properties and analysis. In: *Polymer Optical Fibres*. Elsevier, pp. 153–186.

Zhang, T. and Yang, H., 2018. *High efficiency plants and building integrated renewable energy systems: Building-integrated photovoltaics (BIPV)*,

Zhang, W., Webb, D.J. and Peng, G.D., 2012. Investigation into time response of polymer fiber bragg grating based humidity sensors. *Journal of Lightwave Technology*, 30(8), pp.1090–1096.

Zhong, N. et al., 2016. Effect of heat treatments on the performance of polymer optical fiber sensor. *Optics Express*, 24(12), p.13394.

Zhong, N. et al., 2013. Effects of surface roughness on optical properties and sensitivity of fiber-optic evanescent wave sensors. *Applied Optics*, 52(17), pp.3937–3945.

Zhong, N. et al., 2015. Temperature-independent polymer optical fiber evanescent wave sensor. *Scientific Reports*, 5(1), p.11508.

Zhou, K., Chen, X., Zhang, L. and Bennion, I., 2004. High-sensitivity optical chemsensor based on etched D-fibre Bragg gratings. *Electronics Letters*, 40(4), p.232.

Zhu, S. et al., 2016. High sensitivity refractometer based on TiO2-Coated adiabatic tapered optical fiber via ALD technology. *Sensors (Switzerland)*, 16(8), pp.1–11.

Ziemann, O., Krauser, J., Zamzow, P.E. and Daum, W., 2008. *POF Handbook*, Springer Berlin Heidelberg, Berlin, Heidelberg.

Zubel, M.G. et al., 2016. 3D printed sensing patches with embedded polymer optical fibre Bragg gratings. *Sixth European Workshop on Optical Fibre Sensors*. 30 May 2016 p. 99162E.

Zubia, J. and Arrue, J., 2001. Plastic Optical Fibers: An Introduction to Their Technological Processes and Applications. *Optical Fiber Technology*, 7(2), pp.101–140.

APPENDIX E

LIST OF PUBLICATIONS

Journal with Impact Factor

1. M.S. Moslan, M.H.D. Othman, A. Samavati, M.A.M. Salim, M.A. Rahman, A.F. Ismail, H. Bakhtiar, M. N. M. Sokri. A new potential polymeric cladding material for polycarbonate fibre optic core for high temperature use, *Optical Fiber Technology, (***Q2, IF 2.530***)*

2. M.S. Moslan, M.H.D. Othman, A. Samavati, M.A.M. Salim, M.A. Rahman, A.F. Ismail, H. Bakhtiar, Fabrication of polycarbonate polymer optical fibre core via extrusion method: The role of temperature gradient and collector speed on its characteristics, *Optical Fiber Technology*. 55 (2020) 102162. (**Q2, IF: 2.530**)

Indexed Journal

1. M.S. Moslan, M.H.D. Othman, A. Samavati, M.A.M. Salim, M.A. Rahman, A.F. Ismail, H. Bakhtiar, Fabrication of polycarbonate-based polymer optical fibre cladding: Effect of different solvents, *Malaysian Journal of Fundamental and Applied Sciences*, 15 (2019), 795-798. (**Indexed by Scopus**)