TEMPERATURE AND STRAIN SENSING UTILIZING FLUORESCENCE IN ERBIUM-DOPED PHOTONIC CRYSTAL FIBER

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Dedicated to my beloved family, especially my husband; Mohd Hasrat Bin Sabiran, my daughter; Irdina Amani Binti Mohd Hasrat, my mother; Noraini Binti Adnan, my father; Mahad Bin Ayem, and my siblings who have encouraged, supported, guided and inspired me throughout my journey of education.

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ABSTRACT

This thesis reports a research on the development of erbium-doped photonics crystal fiber (PCF) for simultaneous strain and temperature measurement. Particular focus is given to overcome the existing issue in conventional optical fiber sensor constructed with single mode fiber (SMF) which is dependent on the surrounding temperature. This behavior apparently will result in the incapability of distinguishing strain and temperature measurement. A new sensing scheme is proposed as an alternative technique that allows discrimination of strain and temperature measurement by utilizing the fluorescence of erbium-doped PCF. The erbium-doped PCF structure is modeled and simulated using COMSOL Multiphysics software to determine the main characteristics of the PCF in terms of the effective refractive index and confinement loss. The erbium-doped PCF sensor is developed based on a manual splicing recipe which consists of a short fusion time of 0.4 s, low power electric arc of 70 a.u, gap between PCF and SMF of 14.2 μm and an axial offset position of 12.1 μm. The proposed sensor scheme is developed based on two different interrogations which are the intensity-based interrogation and combination of intensity and wavelength-based incorporating FBG interrogation. Fluorescence ratio techniques are studied over a temperature range of 30-150 ℃ while the intensity/wavelength changes are studied over a strain range of 200-850 $\mu\varepsilon$. Both interrogations results are analyzed using matrix method for strain-temperature de-convolution. Intensity and wavelength-based interrogation shows further significant improvement in average temperature error of 0.0087 ℃ and average strain error of -14.7402 $\mu\varepsilon$ as compared to the conventional erbium-doped fiber. Thus, this sensor is capable of measuring a range of parameters and has potential in implementing discriminative strain and temperature sensing systems in the future.

ABSTRAK

Tesis ini melaporkan satu kajian mengenai pembinaan gentian kristal fotonik (PCF) terdop-erbium untuk pengukuran regangan dan suhu secara serentak. Fokus khusus yang diberikan untuk mengatasi isu yang wujud dalam pengesan gentian optik konvensional yang dibina dengan gentian mod tunggal (SMF) adalah kebergantungan pada suhu sekeliling. Hal ini akan mengakibatkan ketidakupayaan untuk membezakan pengukuran regangan dan suhu. Skim pengesan baru dicadangkan sebagai salah satu teknik alternatif yang dapat membezakan pengukuran regangan dan suhu dengan menggunakan pendarfluor PCF terdop-erbium. Struktur PCF terdop-erbium dimodelkan dan disimulasikan menggunakan perisian COMSOL Multiphysics untuk menentukan ciri-ciri utama PCF dari segi indeks biasan berkesan dan kehilangan kurungan. Pengesan PCF terdop-erbium dibina berdasarkan resipi pencantuman manual yang mengandungi masa lakuran yang pendek sebanyak 0.4 saat, kuasa elektrik lengkuk yang rendah sebanyak 70 a.u, jarak antara PCF dan SMF sebanyak 14.2 µm dan posisi paksi offset sebanyak 12.1 µm. Skim pengesan yang dicadangkan dibina berdasarkan dua interogasi berlainan iaitu interogasi berdasarkan keamatan dan gabungan antara interogasi berdasarkan keamatan dan panjang gelombang menggabungkan FBG. Teknik nisbah pendarfluor dikaji ke atas julat suhu sebanyak 30-150 ºC manakala perubahan keamatan/panjang gelombang dikaji ke atas julat regangan sebanyak 200-850 $\mu\varepsilon$. Kedua-dua keputusan interogasi dianalisis menggunakan kaedah matrik bagi penyahkonvolusi regangan-suhu. Interogasi berdasarkan keamatan dan panjang gelombang menunjukkan lebih peningkatan yang signifikan di dalam ralat suhu purata sebanyak 0.0087 ºC dan ralat regangan purata sebanyak -14.7402 $\mu\varepsilon$ jika dibandingkan dengan gentian terdop-erbium yang lazim. Dengan itu, pengesan ini berupaya untuk mengukur julat parameter dan mempunyai potensi di dalam melaksanakan sistem pengesan bagi membezakan regangan dan suhu di masa hadapan.

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LIST OF ABBREVIATIONS

ASE	-	Amplified Spontaneous Emission
CO_2	-	Carbon Dioxide
CW	-	Continuous Waveform
DNA	-	Deoxyribonucleic Acid
FBG	-	Fiber Bragg Grating
FEM	-	Finite Element Method
FIR	-	Fluorescence Intensity Ratio
FL	-	Fluorescence Lifetime
FPPR	-	Fluorescence Peak Power Ratio
GSA	-	Ground State Absorption
LPG	-	Long Period Grating
MFD	-	Mode Field Diameter
MI	-	Modal-Interference
MMF	-	Multi-Mode Fiber
MOF	-	Microstructured Fiber
MZI	-	Mach-Zehnder Interferometer
OSA	-	Optical Spectrum Analyzer
PCF	-	Photonic Crystal Fiber
PML	-	Perfectly Matched Layer

PBG	-	Photonic Band-Gap
RI	-	Refractive Index
SEM	-	Scanning Electron Microscope
SMF	-	Single Mode Fiber
TIR	-	Total Internal Reflection

LIST OF SYMBOLS

a_R - temperature constant due to the fluorescence ratio

a_B - temperature constant due to the intensity/Bragg wavelength changes

A - cross-sectional area of the fiber cladding

A_i - oscillator strength

c_B - strain constant due to the intensity/Bragg wavelength changes

c_R - strain constant due to the fluorescence ratio

C - pre-exponential constant

d - diameter of PCF air hole

e - layer thickness of PML

E - electric field

EA - oscillator strength for erbium

El - oscillator wavelength for erbium

g - acceleration due to gravity

g_{20} - degeneracy of the upper level

g_{10} - degeneracy of the lower level

H - magnetic field

I_{core} - light intensity in the core mode

I_{clad} - light intensity in the cladding mode

k - Boltzmann’s constant

k_0 - free space wave number

l_i - oscillator wavelength

L - geometry length of the MZI

L_c - confinement loss

m - mass

n - refractive index

N - number of ions

r_{in} - internal radius of PML

R - reflection coefficient

SA - oscillator strength for silica

Sl - oscillator wavelength for silica

T - temperature

X - doping concentration

Y - young’s modulus

ω - angular frequency

ω_{pcf} - MFD of PCF

ω_{smf} - MFD of SMF

ω_{20} - angular frequencies of the upper fluorescence radiation

ω_{10} - angular frequencies of the lower fluorescence radiation

α - butt-coupling insertion loss

α_{20} - temperature-independent decay rates of upper level

α_{10} - temperature-independent decay rates of lower level

Δn_{eff} - difference of the effective refractive indices

ΔE - energy gap level between the emissions

ΔT - change in temperature

$\Delta \epsilon$ - change in applied strain

Λ - periodic length between the holes

ϵ - strain

ε_0 - permittivity of vacuum

μ_0 - permeability of vacuum

σ_e - electric conductivity

σ_m - magnetic conductivity

ρ - distance from the beginning of PML

λ - operating wavelength

CHAPTER 1

INTRODUCTION

1.1 Background of Research

Fiber optic sensor technology has been and increasingly exploited by the research community because of its relatively simple design, low power consumption, low cost, relatively low maintenance cost, and the flexibility it offers. Optical fiber sensors show superior potential for many applications such as biosensor for Deoxyribonucleic Acid (DNA) quantification (Gonçalves *et al.,* 2016), fiber optic seismic sensor (Liu *et al.*, 2015), structural health monitoring (Petrovic *et al.,* 2016), and medical monitoring (Poeggel *et al.,* 2015).

Recently, a new class of waveguide, photonic crystal fibers (PCFs) has become an interesting and extensively developed subject in the worldwide optical field research, leading to a large variety of its designs and applications (Liu *et al.*, 2013). The PCFs which is also known as microstructured fibers (MOFs) are distinguished from the standard “step-index”optical fibers. PCFs cladding are formed by low refractive index inclusions, such as air holes, that run along to the entire fiber core length. PCFs have unique properties which are frequently superior to traditional fibers’ parameters such as lower bending losses, better chromatic dispersion compensation and endlessly single mode light propagation for a very broad wavelength range (Stepien *et al.*, 2014).

Furthermore by appropriate selection of fibers' microstructure properties such as the hole size, distance between holes – lattice pitch, geometry and the air holes position, PCFs can be fabricated with specific properties.

PCF can be designed to be single mode for a wide range of wavelengths compared with conventional fiber, whereas special geometries can provide high birefringence to these types of waveguides. As a result of the absence of rigid boundaries at the core-cladding interface, light travels in the same material minimizing material dispersion effects; this plays a strong influence on the wave-guidance of conventional optical fibers (Koutsides *et al.*, 2012). These interesting characteristics turn PCF to critical components in new generation optical sensing applications. In the previous years, a number or techniques have been presented to measure multiple measurands. Fiber Bragg Grating (FBG) is an established technique which can be incorporated into PCFs based sensor to further enhance sensing capability. The continuing research, by various groups around the world, into the development of optical fiber sensors suitable for the simultaneous measurement of temperature and strain indicates the importance of this issue to many areas of technology.

1.2 Problem Statement

A number of techniques involving standard single mode fiber (SMF) have been demonstrated to measure a wide set of strain and temperature parameters. However, the main problem encountered by traditional optical fiber sensors incorporating FBG is the incapability of distinguishing strain and temperature. It is known that FBG is sensitive to both parameters, and therefore require temperature compensation mechanism. Meanwhile, is virtually insensitive to temperature as the core and cladding is made of only one material and also due to the air hole structure of the pure silica PCF (Najari *et al.*, 2015), hence suits for strain measurement. A sensing technique utilizing a FBG written on a conventional single-mode fiber and a long-period grating (LPG) written on a PCF is demonstrated (Zhao *et al.*, 2009). In the system, the wavelength change of the FBG with environmental temperature is transferred to the intensity of the output via the LPG.

Other instance, PCF Bragg grating sensing scheme is demonstrated for simultaneous measurement of strain and temperature. By writing gratings with similar Bragg wavelengths into two sections of PCF, and filling one of them with alcohol, different temperature sensitivities are obtained while leaving the strain sensitivities similar (Naeem *et al.*, 2014). In order to use the two similar PCF-FBGs for simultaneous sensing of strain and temperature, the air holes of one of the PCF-FBG are filled with alcohol (methanol) which in turns shifts its Bragg wavelength. However, these sensors required two separate elements in one sensor system to allow for temperature compensation purposes. Therefore, a new sensing scheme is proposed as an alternative technique which allows strain and temperature measurement by implementing erbium-doped PCF as a sensor. The erbium ion in the PCF is used to produce fluorescence in the emission band which is independent of temperature and results in the development of temperature as well as strain sensor. Besides that, it is proven that the strain sensitivity of the air-silica PCF sensors is higher than conventional SMF based sensors but the temperature sensitivities of the PCF sensors are much lower (Najari *et al.*, 2015).

1.3 Objectives of Research

This research concentrates on a configuration in which both ends of the erbium-doped PCF are spliced to SMFs. Based on the above mentioned research problem statement, the research objectives can be specified as:

1) To model and simulate the erbium-doped PCF in order to obtain effective refractive index of the fiber.

2) To develop a sensing scheme based on erbium-doped PCF which is capable of discriminating strain and temperature measurement.

3) To attain improvement in error resolution and sensitivity for the developed erbium-doped PCF sensor via matrix analysis.

1.4 Scope of Research

This research starts with detailed literature and technology reviews. The erbium-doped PCF structure is modeled and simulated using a commercially available finite element software tool; COMSOL Multiphysics software to characterize the PCF in term of the effective refractive index and confinement loss. The erbium-doped PCF sensor is developed through a splicing process which is tailored to this special fiber in term of its fiber handling and machine settings which differ from splicing SMF to SMF, such as reduced arc power and shortened fusion time of 0.2-0.5s. Optimization of a fused splice between a PCF and SMF, using a conventional fusion splicer, is performed. Next, the preparation of instrumentation and experimental platform is executed. This is achieved by calibrating a 974 nm pump laser to avoid excess power into the erbium-doped PCF sensor or other devices and components that can cause damaged. Selection of laser pump power is also carry out in this work in order to determine the suitable power which is set fixed throughout the whole experiments.

Then, the developed erbium-doped PCF sensor is centered in a stabilized oven for calibration tests in order to measure the temperature via two types of fluorescence techniques which are the Fluorescence Intensity Ratio (FIR) and Fluorescence Peak Power Ratio (FPPR). The fluorescence intensity of the emission at wavelengths range of 1525-1535 nm and 1545-1555 nm in the erbium-doped PCF sensor is studied as a function of temperature, over the range of 30-150 ^{o}C, using a 974 nm laser diode. A pulley system is used to apply a strain range of 200-850 $\mu\varepsilon$ to the erbium-doped PCF sensor whereby the mass that is added determined the overall strain exerted on the test fiber. The experimental results are analyzed based on two different configurations which are the intensity-based interrogation and combination of intensity and wavelength-based incorporating FBG interrogation. Both interrogations are analyzed using matrix method for strain-temperature de-convolution and the performances are observed in term of the sensitivity and error values of the sensor.

1.5 Significances and Contributions

The measurement of both temperature and strain is highly desirable in a range of industrial applications, e.g., structural health monitoring of composite structures in various temperature environments (Park *et al.,* 2009). In order to develop and implement this scheme, a thorough understanding of the configuration which involves fluorescence ratio technique of the erbium-doped photonic crystal fiber is crucial.

The first contribution of this research work is the proposed sensor scheme developed based on two different configurations which are the intensity-based interrogation and combination of intensity and wavelength-based incorporating FBG interrogation. Both interrogations are analyzed using matrix method for strain-temperature de-convolution. Since PCF is insensitive to temperature due to the low thermo optic coefficient, therefore FIR and FPPR technique is used to measure temperature utilizing the fluorescence in the erbium-doped PCF. Moreover, fluorescence ratio technique has the advantage of using strain-independent temperature measurement allowing for increased flexibility in the de-convolution of temperature and strain. Implementing PCF using fluorescence ratio technique has not been developed yet based on our knowledge for such dual temperature and strain measurement.

The second contribution of this research work is the optimization of splicing and selection of suitable pump power. The sensor for dual strain and temperature measurements are based on erbium-doped PCF which is spliced between two SMF fibers using conventional fusion splicer machine. A manual recipe is developed to fusion splice the PCF and SMF which consists of a short fusion time, low power electric arc, smaller gap between PCF and SMF, and an axial offset position. Other than that, the suitable pump current of the 974 nm laser diode is determine such that the effect of lasing is avoided in this work.

The third contribution of this research work is the modeling and designing of this particular erbium-doped PCF using COMSOL software which has not been developed yet based on our knowledge. This erbium-doped hexagonal PCF with 7 rings of air holes has a central core region which is perturbed by erbium doping. The refractive index of erbium doped silica is computed by modifying the equation from literature based on the coefficients for erbium. The effective refractive index of the erbium-doped PCF is determine to minimize the internal reflection in the fiber. This information is useful for the development of the erbium-doped PCF sensor whereby the erbium-doped PCF is spliced to SMF.

1.6 Overview of Thesis

This thesis describes the temperature and strain sensing of a developed erbium-doped PCF sensor. The fluorescences in the erbium-doped PCF sensor are utilized for temperature measurement. In this Chapter 1, the background and fundamental problem of this research work are discussed. The objectives and scope of this work are explained in detail. The significant and contributions in this work is also presented. Chapter 2 introduces the comprehensive literature review on the fundamental PCF and technologies apply. This chapter gives an overall picture of current technologies of PCF sensors and their applications. A review of various PCF sensor configurations for temperature and strain sensing is presented and the technologies employed are examined and discussed. In this chapter, the theoretical background such as fundamental of the fluorescence techniques are explained. Various splicing techniques are also reviewed.

Chapter 3 discusses on the modeling of erbium-doped core PCF which has 7 rings of hexagonal air holes. The PCF structure with a perfectly matched layer (PML) is modeled and simulated using Finite Element Method (FEM) via COMSOL Multiphysics software. The PML is optimized by varying the internal radius and the thickness of the layer. Modal properties of the PCF have been characterized in term of its effective index of the supported fundamental mode and confinement loss. The effective refractive index of the erbium-doped PCF is determined to minimize the internal reflection in the fiber. This information is useful for the development of the erbium-doped PCF sensor whereby the erbium-doped PCF is spliced to SMF.

Chapter 4 discusses the instrumentation and experimental platform required before performing the calibration tests for the developed erbium-doped photonic crystal fiber sensor. This PCF fiber sensor is developed by splicing the PCF to SMF using conventional fusion splicer machine. Other than that, this chapter also discusses the laser calibration which is necessary in order to avoid excess power into the sensor or other devices and components that can cause damage. Selection of laser pump power is also discussed in this chapter in order to determine the suitable power which is set fixed throughout the whole experiments. The final sub-topic in this chapter is the experimental setups for temperature and strain measurement.

Results and analysis of the experimental works for the developed erbium-doped PCF sensor are discussed in Chapter 5. The experimental results are analyzed based on two different configurations which are the intensity-based interrogation and combination of intensity and wavelength-based incorporating FBG interrogation. FIR and FPPR technique is used to measure temperature utilizing the fluorescence in the erbium-doped PCF. Both interrogations are analyzed using matrix method for strain-temperature de-convolution and the performances are observed in term of the sensitivity and error values of the sensor. The conclusions, contributions and future work of this investigation are summarized in Chapter 6.

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