AN OUTDOOR FIBRE BRAGG GRATING TEMPERATURE SENSOR

SUZAIRI BIN DAUD

UNIVERSITI TEKNOLOGI MALAYSIA

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SUZAIRI BIN DAUD

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To my beloved family…

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ABSTRACT

A prototype outdoor fibre Bragg grating (FBG) temperature sensing system based on a commercial FBG has been designed, constructed, developed, and its performance evaluated. The commercial FBG sensor head has a center wavelength of 1553.865 nm, 0.24 nm bandwidth, >97 % reflectivity, and a length of (3.0±0.1) cm. In order to reduce the optical losses of the FBG system, the shortest optical fibre path used was (55.0±0.1) m. The temperature sensitivity of the system was evaluated for different placement heights from the rooftop floor with and without the presence of focusing elements. The TLS was used to provide the broadband light source via a fibre optic cable of wavelength 1550 nm. The OSA was used to display the transmission and reflection spectrum from which the Bragg wavelength, λ_B, bandwidth, and power dip are obtained. The transmission spectrum was obtained through direct connection to the FBG and the reflection spectrum using a (2x2) 3dB coupler. The Bragg wavelength change with temperature changes was used to determine the FBG system's performance. Results obtained shows that $\Delta\lambda_B$ is directly proportional to temperature changes for both transmission and reflection spectrum with and without focusing elements at different placement heights. The gradient of $\Delta\lambda_B$ versus temperature provides the sensitivity of the FBG system. The average sensitivity of the FBG sensor system measured was 10.0 pm/°C without any focusing element. It has an average of 12.5 pm/°C when the FBG sensor head was focused with a convex lens and 13.9 pm/°C when focused with a hand lens. The FBG sensor system sensitivity was increased when a hand lens was used. The sensitivity is constant irrespective of the FBG sensor head position from the floor. Thus, a prototype FBG sensing system has been developed for outdoor temperature measurements.

ABSTRAK

Satu prototaip gentian parutan Bragg (FBG) bagi sistem penderia suhu di kawasan terbuka menggunakan FBG komersil telah direkabentuk, dibangunkan, dimajukan, dan prestasinya dinilai. Panjang deria FBG komersil tersebut mempunyai panjang gelombang Bragg 1553.865 nm, jalur lebar 0.24 nm, pantulan >97%, dan (3.0±0.1) sm panjang. Bagi mengurangkan jumlah kehilangan pada sistem ini, gentian optik sepanjang (55.0±0.1) m telah digunakan. Kepekaan suhu sistem ini dinilai pada ketinggian yang berbeza dari lantai bumbung dengan menggunakan kanta penumpu dan tanpa meggunakan sebarang elemen penumpu. TLS memancarkan sumber cahaya pada nilai tertentu menerusi kabel gentian optik dengan panjang gelombang 1550 nm. OSA pula memaparkan spektrum pancaran dan pantulan yang mana panjang gelombang Bragg, $\Delta\lambda_B$, jalur lebar, dan kuasa junam dapat diukur. Spektrum pemancar diperoleh melalui penyambungan terus dengan FBG dan spektrum pantulan pula diperoleh dengan menggunakan gandingan (2x2) 3dB gentian optik. Perubahan panjang gelombang Bragg terhadap perubahan suhu persekitaran digunakan untuk menilai kepekaannya. Keputusan yang diperoleh menunjukkan perubahan panjang gelombang Bragg adalah berkadar langsung dengan perubahan suhu bagi kedua-dua spektrum pancaran dan pantulan, dengan atau tanpa elemen pemfokus, pada ketinggian berbeza. Kecerunan graf $\Delta\lambda_B$ lawan suhu memberi nilai kepekaan sistem tersebut. Purata kepekaan sistem penderia FBG tersebut adalah 10.0 pm/°C bagi sistem tanpa elemen pemfokus. Purata kepekaannya bernilai 12.5 pm/°C apabila penderia tersebut ditumpukan dengan kanta cembung dan 13.9 pm/°C bagi sistem yang ditumpukan dengan kanta tangan. Kepekaan sistem penderia FBG tersebut meningkat apabila kanta tengan digunakan. Kepekaannya adalah malar dengan tidak dipengaruhi oleh kedudukan FBG tersebut. Maka, satu prototaip sistem penderia FBG bagi pengukuran suhu luar telah berjaya dibangunkan.

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LIST OF SYMBOLS

a	-	Core radius
b	-	Wavelength position at 0 °C
CMT	-	Coupled-mode theory
d	-	Power dip
dB	-	Decibel
DNA	-	Acid deoksibonukleid
E	-	Electric field
EMI	-	Electromagnetic interference
FBG	-	Fibre Bragg grating
FBGs	-	Fibre Bragg gratings
FOS	-	Fibre optic sensor
$FWHM$	-	Full width at half maximum
H	-	Magnetic field
HiBi	-	High birefringent
$\vec{K}$	-	Grating momentum vector
$\vec{k}$	-	Propagating constant vector
k	-	Propagating constant
$\vec{k}_1$	-	Modal wavevector of the forward-propagating wave
$\vec{k}_2$	-	Modal wavevector of the backward-propagating wave
L	-	Grating length
MHz	-	Mega Hertz
M_p	-	Fraction of fibre mode power
N	-	Number of grating plane
NA	-	Numerical aperture
nm	-	nanometer
n_{cl}	-	Cladding refractive index

n_{co}	-	Core average index
n_{eff}	-	Effective refractive index
n_o	-	Average refractive index
n_1	-	Refractive index of fibre core
n_2	-	Refractive index of fibre cladding
OSA	-	Optical Spectrum Analyzer
$pm/°C$	-	pikometer per degree Celsius
R	-	Reflectivity
$R(L,\lambda)$	-	Reflectivity in the function of length and wavelength
s	-	Fringe visibility of the index change
T	-	Temperature
TLS	-	Tunable Laser Source
UV	-	Ultraviolet
UVA	-	Ultraviolet A
UVB	-	Ultraviolet B
UVC	-	Ultraviolet C
z	-	Distance along the fibre longitudinal axis
ε	-	Permittivity
μ	-	Permeability
ε_z	-	Strain
α	-	Thermo-expansion coefficient
ξ	-	Thermo-optic coefficient
Ω	-	Coupling coefficient
Λ	-	Grating period
Λ_g	-	Grating spacing
Λ_{pm}	-	Phase mask period
λ	-	Wavelength
λ_B	-	Bragg wavelength
λ_{in}	-	Incident light
$\lambda_{B,0}$	-	Nominal Bragg wavelength
λ_o	-	Initial wavelength
δL	-	Change of length
δn_{eff}	-	Change of refractive index
Δk	-	Detuning wavevector

Δn	-	Dept of index modulation
ΔT	-	Temperature change
$\Delta\lambda_B$	-	Bragg wavelength shift
°C	-	Degree Celsius
°F	-	Degree Farenheigh
%	-	Percentage

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Over the last five decades, fibre optic sensors (FOS) have emerged as modern device in sensing and telecommunication technologies. FOS can be classified as fluorescent/spectrally-based, intensity-based, or interferometric. Fluorescent-decay temperature sensor, blackbody radiation temperature sensor, Fabry-Perot temperature sensor, interferometric temperature sensor, polarimetric temperature sensor, and dual mode temperature sensor are examples of sensors used in fibre optic temperature sensing. Fibre Bragg grating (FBG) has the unique advantage as an fibre optic temperature sensor as compared with all other temperature sensors (Neil, 1990).

FBG is used in measuring the temperature accurately in a variety of environment (Yonghang, 2004) which includes in harsh environment, underground, and also disaster places. Fibre Bragg grating is a type of distributed Bragg reflector constructed in a short segment of optical fibre that reflects a particular wavelength of light and transmits all the other wavelengths. This is achieved by appending a periodic variation to the refractive index of the fibre core, which generates a wavelength of specific dielectric mirror. Thus, an FBG can be use as an inline optical filter to block certain wavelength or as a wavelength-specific reflector.

The most important innovation of the 1990's in FOS is the development of FBG sensors. Fibre Bragg grating can used as a sensor because of its excellent unique properties. FBG emerges as an important technology in fibre optic sensing due to its smart structure, excellent linear characteristics, immune to electromagnetic interference (EMI), low fibre loss, and other outstanding advantages (Lai *et al.*, 2002). Nowadays, decent and sophisticated techniques in temperature measurement become very important and necessary for safety precautions in industrial requirements (Bowei, 2004).

The FBG sensitivity measurements will be assessed for different FBG's position from the rooftop floor using different focusing elements at periods of the day. The research will examine the effect of different focusing elements, FBG positions, and temperature variations on the sensor head of the FBG. Measurements made will be based on the transmission and reflection spectrum of the FBG.

1.2 Background of Study

A sensor is a device that measures a physical quantity and converts it into a signal which can be read by an instrument. For example, mercury in glass thermometer converts the measured temperature into expansion and contraction of the liquid which can be read on a calibrated glass tube. A thermocouple converts the temperature measurement to an output voltage which can be read by a voltmeter. For accuracy purposes, most sensors are calibrated against known standards.

Temperature is an important and most commonly measured parameter in everyday applications. Traditionally, the semiconductor sensor, platinum resistance sensor, thermistor, and thermocouple are most commonly utilized for temperature measurements. For most applications, these conventional temperature sensors can be adequate for its purpose. However, these temperature sensors are not reliable due to the lack of intrinsic safety, their characteristics of electrically active, and poor lifetime at excessive temperatures (Yonghang, 2004). Furthermore, these conventional temperature sensors are all point sensors. In other words, they are localized sensors, which can only provide temperature reading over a small area rather than providing an overall temperature profile (Udd, 1995). These sensors are also suitable for the passive multiplexing, but difficult in practice, due to size limitations (Xiaopei *et al.*, 2004).

Optical fibre offers a number of distinguishing and excellent advantages over conventional sensors. Fibre Bragg grating (FBG) sensor is one of the most important and useful optical fibre sensors. The concept of FBG was discovered three decades ago by Hill and his co-workers (Hill, 1978). However, most of the recognized pioneering work about FBG and its applications were only published a decade later after it's discovery by a group of researchers at United Technology Research Centre (Meltz *et al.*, 1989).

FBG sensors are dielectric and virtually immune to electromagnetic interference (EMI). It can withstand against hostile environment, including in high and excessive temperature. It can be used to measure high temperature, until 1000 °C (Hirayama *et al.*, 2000). It is also utilized as a distributed sensor. In principle, distributed sensors are different from point sensors. Here the parameter of interest is measured with certain spatial resolution at any points along a single optical fibre. They would permit the use of power sensors and represents more effective use of optical fibre that are used for both measurements and data transmission, which allows them to become more attractive.

FBG sensors can be incorporated into optical fibre cables. These sensors can be embedded into new structure or surface bonded onto an existing structure. This allows real time monitoring of structures (Tahir *et al.*, 2005), ultimately leading to truly 'smart', and provide fatigue data for subsequent analysis (Everal, 2000). FBGs are able to play a crucial role in sensing technology, due to their unique smart structure (Lai, 2002).

1.3 Problem Statement

The main motivation of this research is to design, construct, and develop temperature sensor using a commercial fibre Bragg grating (FBG) sensor under outdoor condition. To this end, a commercial germanium-doped silica fibre Bragg grating is used. This research will examine the effect of temperature variations on the characteristics of an outdoor FBG temperature sensor. How does the characteristics of FBG sensor respond to changes under different environment conditions and placement heights of FBG? How does the focusing elements such as convex lens and hand lens affect the sensitivity of FBG? These investigations can be used to determine the performance of FBG sensor for outdoor temperature measurement. Its performance will be evaluated based on the transmission and reflection spectrum.

1.4 Objective

The objective of this research is to design, construct, and develop an outdoor FBG temperature sensor system for different FBG placement heights from the rooftop floor. The effect of FBG at different heights from the rooftop floor will be evaluated. The research will also analyze the effect of focusing elements on the FBG sensor head based on the transmission and reflection spectrum.

1.5 Scope of Study

This research starts with a literature review on FBG. The literature review will focused on temperature sensing of FBG and its sensitivity. The theory involved in temperature sensing will be discussed. The principle of FBG is based on coupled-mode theory (CMT). The FBG spectrum at room temperature were taken for both transmission and reflection spectrum as the reference for Bragg wavelength shift. The measurement of FBG temperature sensing was made at the different placement heights of FBG with different focusing elements used at the sensor head. The convex lens and hand lens were used as the focusing elements in this research. The performance or sensitivity of the FBG will be analyzed in terms of the Bragg wavelength shift.

1.6 Significance of Study

This research enables us to understand FBG temperature sensing performance by examining the characteristics and properties of the FBG. Initially studies shows that there are rapid fluctuations in outdoor temperature. The sudden change in outdoor conditions such as temperature variation, rain, and effect of wind blowing may affect the stability of the reading.

With the increasing needs for health monitoring in structures such as bridges, tunnels, highways, dams, aircraft wings, and spacecraft fuel tanks, it is imperative to design and develop an effective sensor system which can detect any sudden changes in strain, pressure, and temperature. The practical challenges here may include decoupling at different sensing parameters for long term thermal stability of the FBG under outdoor environment. This enables us to apply the FBG temperature sensor in a variety of fields, such as medical, construction, manufacturing, industry, and many more.

1.7 Organization of Study

This thesis consists of six chapters and begins with a brief introduction of the research background and work undertaken as described in Chapter 1. It includes the background study, problem statement, objective, scope, and significance of the study. The literature review on FBG fundamental, an overview of FBG for temperature sensing, the properties of sun radiation and spectral wavelength are described in

Chapter 2. In Chapter 3, the theory of FBG will be discussed in detail. This includes the coupled-mode theory, the properties, optical response, and characteristics of FBG. Chapter 4 describes the FBG experimental set-up and the research methodology used in this research. Chapter 5 gives the results, analysis, and discusses the performance testing evaluation of FBG for outdoor temperature sensing. The Bragg wavelength response with respect to the temperature variation is analyzed. Parameters such as sensitivity, bandwidth, and reflectivity are analyzed for different FBG's height placement from the rooftop floor and for different focusing elements placed on the FBG sensor head. Finally, Chapter 6 provides the conclusion of this study and suggestion for further work.

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