DEVELOPMENT OF ALL-FIBER LASER INTRACAVITY WITH TAPERED BIOSENSOR

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By

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The development of biosensors based on tapered optical fibers has shown promising results of high sensitivity and specificity. The sensing principle lies within the reaction of evanescent field driven from the tapering of the optical fiber extends into the surrounding medium and is highly sensitive to any changes in the refractive index within the vicinity of the tapered optical fiber, making it suitable to be used as a sensor. Recently, single mode tapered fiber has attracted great attention from researchers due to its high sensitivity and power-independent spectral measurements. However, the complexity of analyzing the multi-fringe optical spectrum makes it prone to misinterpretation. This research work demonstrates the integration of a bio-functionalized tapered fiber sensor in a fiber laser cavity for detection of biological molecules. The significance of integrating the sensor within the fiber laser cavity lies in the simplification of the sensing results. To ensure that the taper profile can maintain a single wavelength output during measurements, different taper profiles were tested with varying concentration of sodium chloride (NaCl) and taper profile with 15 μm waist diameter and waist length of 10 mm was found to be the best. Subsequently, tapered fiber using the optimum taper profile was functionalized with biotin and its sensing performance in ring cavity EDFL setup was then assessed by immersing the tapered fiber biosensor into various concentration of avidin ranging from 1 to 10 pM at the maximum pump power of 200 mW. The proposed setup obtained a sensitivity of 1.02 nm/pM with a detection limit of 1 pM. Afterwards, the bio-functionalized tapered fiber in ring cavity EDFL setup was tested at lower gain condition of 40 mW pump power, which yielded lower sensitivity of 0.4 nm/pM. The sensitivity value deteriorated at low gain condition since the net gain bandwidth was narrower and evanescent field interaction was affected by lower intensity light intensity in the cavity. The realization of a properly packaged all-fiber laser intracavity taper

biosensor can simplify the analysis, translating the results in a single wavelength manner that is more practical without compromising the many qualities of this technology.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

PEMBANGUNAN SEMUA GENTIAN LASER PENDERIA-BIO DENGAN RONGGA TIRUS

Oleh

MAISARAH BINTI MANSOR

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Pembangunan penderia-bio berasaskan gentian optik yang tirus telah menjanjikan keputusan sensitiviti dan spesifisiti yang tinggi. Prinsip penderiaan tertera dalam reaksi yang cepat berlalu dari gentian optik tirus yang diperluaskan ke dalam kawasan sekitarnya dan sangat sensitif terhadap sebarang perubahan dalam biasan indeks berdekatan gentian optik tirus, menjadikan ia sesuai untuk dijadikan sebagai sensor. Baru-baru ini satu mod tirus gentian telah menarik perhatian utama dari penyelidik disebabkan oleh kepekaan yang tinggi dan tidak bergantung kepada kuasa untuk spektrum pengukuran. Walau bagaimanapun, kerumitan menganalisis spektrum optik berbilang pinggiran menyebabkan kepada salah tafsir. Kerja-kerja penyelidikan ini menunjukkan integrasi penderia gentian tirus difungsikan dalam sistem laser untuk mengesan molekul biologi. Kepentingan mengintegrasikan penderia dalam laser gentian memudahkan keputusan penderian. Untuk memastikan profil gentian tirus sentiasa mengekalkan laser tunggal ketika pengukuran, beberapa profil gentian tirus telah diuji dengan pelbagai kepekatan natrium klorida (NaCl) dan profil gentian tirus dengan 15 mikron diameter pinggang dan panjang pinggang 10 mm menjadi yang terbaik. Kemudian, gentian tirus yang mengunakan profil gentian tirus yang terbaik telah difungsikan dengan biotin dan prestasi dari segi penderiaan di laser gentian EDFL telah dinilai dari menyelami penderia-bio gentian tirus ke dalam pelbagai kepekatan avidin antara 1 hingga 10 pM pada kuasa pam yang maksimum 200 mW. Persediaan yang dicadangkan mendapat sensitiviti 1.02 nm/pM dengan had pengesanan 1pM. Selepas itu, serat gentian tirus difungsikan di laser gentian EDFL telah diuji pada keadaan kuasa pam yang lebih rendah iaitu 40 mW yang menunjukkan kepekaan yang lebih rendah sebanyak 0.4 nm/pM. Nilai kepekaan merosot pada kuasa pam rendah kerana nilai penghantaran data sempit dan interaksi oleh medan cahaya dipengaruhi oleh intensiti cahaya yang lebih rendah di dalam kaviti tersebut. Proses merealisasikan system ini membawa kepada pembungkusan semua serat laser antara rongga tirus

penderia-bio dapat memudahkan analisis, menterjemahkan keputusan dengan cara yang lebih praktikal tanpa menjejaskan kualiti yang wujud dalam teknologi ini.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

ASE	Amplified Spontaneous Emission
AWG	Arrayed Waveguide Grating
BSA	Bovine Serum Albumin
C-band	Conventional-wavelength band (1530 nm to 1565 nm)
EDF	Erbium-Doped Fiber
EDFL	Erbium Doped Fiber Laser
EW	Evanescent Waves
FBG	Fiber Bragg Grating
FESEM	Field Emission Scanning Electron Microscopy
FSR	Free Spectral Range
HCPCF	Hollow-Core Photonic Crystal Fiber
L-band	Long-wavelength band (1565 nm to 1625 nm)
LOD	Limit of Detection
MMF	Multi-Mode Fiber
MMI	Multi-Mode Interference
MZFI	Mach-Zender Interferometer
OPM	Optical Power Meter
OSA	Optical Spectrum Analyzer
PBS	Phosphate Buffer Solution
QTF	Quartz Tuning Fork
RI	Refractive Index
SMF	Single Mode Fiber
SMS	Single mode-Multimode-Single mode
SNS	Single mode-No core-Single mode

SPR	Surface Plasmon Resonance
TBF	Tunable Bandpass Filter
UV	Ultraviolet
WDM	Wavelength Division Multiplexer

CHAPTER 1

INTRODUCTION

1.1 Overview

The usage of optical fibers in telecommunications have become crucial since the development of low-attenuation optical fibers for long-distance lightweight transmission within the 1970s [1]. In parallel with the development of fiber waveguides and optical fiber-based communication devices, the function of the optical fiber has been expanded for sensing applications as well. Various sensors have been developed using optical fiber to observe physical and chemical parameters including strain, temperature, vibration, and pH [2][3][4][5]. In general, the sensing capability is achieved by permitting the transmitted light in the optical fiber to move within the sensing medium. The intensity, phase, polarization and wavelength of the transmitted light may be changed due to the different surrounding of sensing medium and can be converted to measurable and quantitative optical signals. Compared with standard electronic sensors, optical fiber sensors provide useful benefit including high sensitivity, small size, light-weight, and immunity to magnetic field interference. The optical fiber sensor also has the ability to operate in high-temperature environments and provides high potential for remote operation [6]. As a result, various types of optical fiber sensors have been developed within the past few decades to facilitate sensing applications in many areas covering environmental monitoring, manufacturing control, national security, aerospace, and biomedical [7].

With the increase of medical specialty and nanotechnologies in recent years, there is an increasing demand for top performance miniaturized sensors to supply sensitive and quick detection of chemical compounds, biomolecules and cells. Standard optical fibers enable restricted access to the evanescent field and show inefficient light-environment interactions usable for sensing applications. An enhancement to induce access to the evanescent fields is by using tapered glass fibre for higher measurement sensitivity, or minimal field exposure for an extended concentration sampling range. The development of single mode optical tapered glass fiber provides an additional and promising answer to satisfy the challenge.

Most of the tapered optical fiber biosensor has been used with fluorescent labels in order to achieve lower detection limit [8]. However, it is important to realize the attractiveness of label-free detection, which includes more rapid results, lower costs, and ease of use. The use of intensity-based tapered optical fiber biosensor has rarely been studied because of the large dependence of transmission on geometry [9]. Aside from intensity-based detection, the use of IR wavelengths with tapered optical fiber biosensor is also feasible. Although IR wavelengths are not typically absorbed by biological species, it may not be necessary to use a wavelength which is absorbed because tapered optical fiber biosensor using spectral profiling method has the ability to detect based on refractive index changes alone, provided that these changes occur close to the surface of the sensing region [10].

1.2 Problem Statement

Single mode tapered fiber has attracted great attention as sensing transducer because the wavelength-based detection mitigates power-influenced instability. The sensor generates spectral fringes that can used for sensing by observing the shift of the fringes. However, the problem is the potential confusion on which peak should be observed as well as the direction of the shift. This leads to complexity in the analysis and makes the reading prone to misinterpretation. Such drawbacks become more critical if the sensor is to be used for medical diagnostic purposes which have very minimal tolerance towards inaccuracies.

1.3 Aim and Objectives

The research work is focused on innovating an intracavity biosensor fiber laser system that can operate as a platform for any type of tapered optical fiber biosensor. The significance of deploying or 'plugging in' the sensor within the intracavity fiber laser system lies in the simplification of the sensing analysis, making the output translation process more practical with no impedance to the original performance of the sensor. The objectives of the study are:

i. To determine the suitable tapered optical fiber parameter for single wavelength laser output
ii. To investigate the sensitivity of the intracavity biosensor system towards determinants within the range of concentration defined by the limit of detection (LOD)
iii. To investigate the impact of gain control towards the intracavity biosensor system.

1.4 Scope of Work

The scope of work in the research is summarized in Figure 1.1. Generally, this research looks into deploying the tapered optical sensor within the intracavity fiber laser system for simplification of the sensing analysis. The single mode tapered optical fiber is picked due to the high sensitivity of the evanescent wave property especially for lights that travel at the waist diameter. The exposed nature of tapered optical fiber creates vast opportunities for customisation and integration with other materials to fit the demands of the sensor field, today. Not only that, the spectral shift-based detection provides accurate, power-independent sensing output. The capability of the system to quantitatively sense difference in the biotin-avidin complex is integral to the success of this work. Different concentrations of avidin are required in order to find the LOD with the aim of attaining pM range of detection. Ten concentrations will then be tested starting from that LOD in order to validate the sensor's response towards changes within that concentration range. Ultimately, the main focus of this research is to explore a more practical and high-performance sensing system feasible for disease detection.

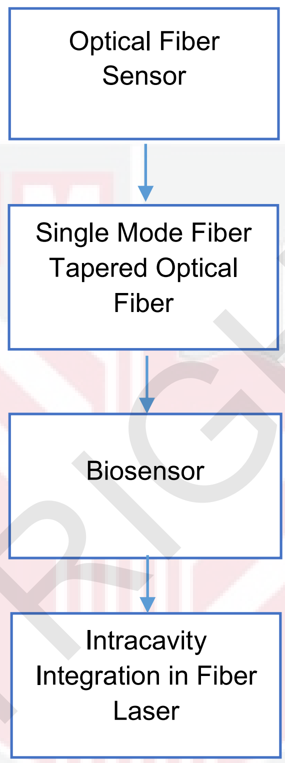

Figure 1.1: Scope of Work

1.5 Organization of Thesis

The organization of this thesis is explained as follows:

Chapter 1 consists of the introduction and overview of the research work. It provides a background on an optical fiber, optical fiber sensing, and bio-functionalized tapered optical fiber sensors. The challenges related to tapered optical fiber biosensor is highlighted along with the aim and the objectives that are formed to address those issues. The scope of work and thesis organization are also included in this chapter.

Chapter 2 introduces the underlying theory relevant to fiber laser and tapered optical fiber sensor. This includes throughout the discussion on used of tapered fiber as a sensor. The emerging technology of intracavity fiber laser within the optical sensing system is also presented in this chapter.

Chapter 3 combines the methodology used in this work and the results obtained from the whole process. Overview of the laser design and explanation on how it operates are provided. The fabrication of the tapered optical fiber and the characterization of its geometrical dimension to obtain suitable FSR in a laser cavity are also detailed. Additionally, details on the functionalization of bio-recognition molecules onto the surface of the tapered optical fiber are included followed by optimization of the surface modification method and ultimately the output post-integration with intracavity fiber laser setup.

Lastly, chapter 4 concludes the research work. All the important findings corresponding to the set objectives are highlighted and recommendations for future work are also given.

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