Notice of the Final Oral Examination
for the Degree of Doctor of Philosophy

of

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“Development and Analysis of Photonic Crystal Fiber
Mach-Zehnder Interferometer for Highly Sensitive
Detection and Quantification of Gases”

Department of Mechanical Engineering

Tuesday, August 25, 2020
10:30 A.M.
Remote Defence

Supervisory Committee:
Dr. Colin Bradley, Department of Mechanical Engineering, University of Victoria (Supervisor)
Dr. Rustom Bhiladvala, Department of Mechanical Engineering, UVic (Member)
Dr. Martin Jun, Department of Mechanical Engineering, UVic (Member)
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Abstract

Gas sensing is essential for safety and maintenance operations in many industries, including power generation, petrochemical, capture and storage technologies, and the food-processing sector. The properties of fiber-optic sensors make them a superior choice for environmental monitoring applications, especially in extreme conditions, and particularly when compared against conventional electro-optical sensors. Their advantageous properties include immunity to electromagnetic radiation, high temperature durability, high sensitivity and the ability for high resolution detection, as well as multifunctional sensing capabilities such as temperature, humidity, pressure, strain, and corrosion. Among different types of interferometers, MZIs have received significant attention because they are robust, compact, and have high levels of precision.

In this dissertation, we present an in-line and compact Mach-Zehnder Interferometer point sensor designed for sensing refractive index. The MZI sensor is developed using photonic crystal fiber and demonstrated for high sensitivity detection and measurement of pure gases. The transmission spectrum of MZI sensors are formed by interference between the cladding and core modes. To construct the device, the sensing element fiber was placed and aligned between two single-mode fibers with air gaps at each side. Great measurement repeatability was shown in the cyclic test for the detection of various gases such as methane and helium. A high resolution of 2.1 E-7 and a sensitivity of 4629 nm/RIU was achieved, which is among the highest reported. The sensitivity of the fabricated MZI sensor increases when the length of the sensing element decreases. In addition, it is shown that response and recovery times of the proposed sensor inversely change with the length of the sensing element fiber, namely solid/hollow core photonic crystal fibers. Furthermore, the temperature sensitivity of the fiber-optic interferometer decreases when the length of the PCF decreases. The proposed sensors have the potential to improve the ability of current technology to detect and quantify pure gases.

Among various gases that were used to evaluate the performance of the proposed gas sensor, carbon dioxide (CO₂) is the greenhouse gas of most immediate concern due to its high atmospheric concentration and long lifetime. Thus, the optical fiber MZI sensor was evaluated for its ability to monitor carbon dioxide concentration. The device was packaged to demonstrate the laboratory-scale monitoring, as well as leakage detection of CO₂ concentration in both
subsurface soil and aqueous environments. Two water resistant but gas permeable membranes were used to package the sensor, to achieve a good balance of CO\textsubscript{2} permeability and water resistance. The spectrum of the sensor did not show any significant degradation over the period of 24 hours in an aqueous environment. At room temperature and atmospheric pressure, the sensor shows the sensitivity of 4.3 pm/ % CO\textsubscript{2}. Considering the measurement device used in this study has wavelength stability of 1 pm, the resolution of the sensor is \sim 0.2\% CO\textsubscript{2}. The experimental study of this work reveals the great potential of the fiber-optic approach for environmental monitoring of CO\textsubscript{2}.

Additionally, a detailed study was conducted to better understand the effect of photonic crystal fiber structure and gap distances on the performance of the fiber-optic gas sensors. This study also explores other potential applications. Three types of sensors were fabricated using the proposed configuration employing 4 mm stub of (i) PCF, (ii) 10 μm HC-PCF, and (iii) 20 μm HC-PCF as the sensing elements. We compared the performance of these sensors for detecting and measuring the quantity of gas present. As the transmission signals correspond to the frequency components in the sensor’s Fast Fourier Transform (FFT) spectrum, the effect of gap distance on the number and amplitude distribution of the modes was examined in an effort to optimize the design elements. Spatial frequency analysis revealed that power is mainly carried by one mode in the solid-core PCF, two dominant modes in the 10 μm MZI, and three dominant modes in the 20 μm MZI. The sensor with 10 μm HC-PCF in the tested RI range had the highest sensitivity, whereas the highest amount of power transmission was recorded for an MZI with solid core PCF. It was concluded that stronger interference occurs by using 20 μm HC-PCF as a sensing element of the MZI, and a higher number of modes can be carried by this fiber. The measurement response and recovery times for all sensors were determined, and it was concluded that the 20 μm HC-PCF sensor has the fastest response/recovery time and the solid core PCF sensor has the slowest. The sensors are highly sensitive to low percentages of CH\textsubscript{4} and CO\textsubscript{2}, making them suitable for greenhouse gas measurement. It should be noted that the main drawback of this sensor is gas selectivity, as its response to the presence of any gas and is not selective.