Chapter 8. Conclusions and Future Work

To fulfill the objective of providing robust and reliable fiber optic pressure sensors capable of operating in harsh environments, this thesis presents the detailed research work on the design, modeling, implementation, analysis, and evaluation of the novel fiber optic self-calibrated interferometric/intensity-based (SCIIB) pressure sensor system. This chapter summarizes the major conclusions obtained during the research. Future research work to further improve the system performance is also outlined in the chapter.

8.1 Conclusions

Upon the detailed description of the principle of the SCIIB sensing technology, it was revealed that the SCIIB sensor system possesses several unique advantages in addition to the general features as a fiber optic sensor system. By self-referencing its two channel outputs, the SCIIB signal processing technique can fully compensate for the fluctuation of source power and the variations of fiber losses. Also by confining the operating range of the sensor within the semi-linear portion of the half interference fringe, the SCIIB sensor achieves extremely high resolution with simple single-processing. Moreover, the phase ambiguity problem is solved. These unique advantages make the SCIIB technology an excellent candidate for harsh environmental sensing applications.

Based on the SCIIB principle, two SCIIB sensor systems were designed and successfully implemented. The low cost multimode SCIIB system operated at 850nm wavelength and is a good solution for short distance applications where the relatively large fiber attenuation is not a concern. The single-mode fiber-based SCIIB system, operating at 1310nm wavelength, can provide accurate remote measurements over a long distance.

In order to achieve all the potential advantages of the SCIIB technology, the novel sensor fabrication system based on the controlled thermal bonding method was proposed, designed, developed, and evaluated. For the first time, high performance fiber optic Fabry-Perot sensor probes can now be fabricated with excellent mechanical strength and temperature stability. The sensor fabrication system uses a CO_2 laser as the heating source to locally fuse the capillary tube and fiber together to form a solid bond. The whitelight interferometry provides the system with the capability of real-time on-line monitoring of the sensor cavity length. The computer controlled stage system allows the accurate adjustment of the sensor cavity length during the sensor fabrication. The integration of these three parts permits the sensor to be fabricated in a controlled fashion and reinforce the sensor's capability when operating in harsh environments. Both high performance multimode and single-mode fiber SCIIB sensor probes have been fabricated using the developed sensor fabrication system. Test results show that the sensors fabricated based on the controlled thermal bonding method have excellent reliability and stability to survive the high pressure and high temperature environment.

The mathematical models of the sensor in response to the pressure and temperature are studied to provide a guideline for optimal design of the sensor probe. The pressure model predicts the correspondence between the sensor gauge length and its dynamic range of pressure measurement. The temperature model reveals that the sensor has a built-in capability of passive temperature compensation. Through the optimal design of the sensor probe, close to zero temperature cross sensitivity can be achieved.

An extensive and detailed noise analysis is also presented to provide a better understanding of the performance limitation of the SCIIB system. The electronic noise analysis indicates that the shot noise and the thermal noise together form the ultimate limit of the system performance. The optical analysis of the system identifies that the error resulting from the random change of state of polarization is the dominant source of error. The optical noise analysis also indicates that the temperature-induced change of the spectral characteristics of the optical bandpass filter contributes the most to the dynamic error of the system. The source spectrum drift and the fiber bending induced spectrum shift can only affect the system performance slightly through the non-centered filtering and the residual interference of the reference channel.

Based on the system noise analysis results, optimization measures are suggested to improve the system performance. The polarization error is reduced significantly by adding a depolarizer to the system. By matching the filter center wavelength to the center of the source spectrum, the measurement error resulting from the non-centered filtering is also reduced dramatically. To compromise the filter spectrum shift effect and the residual interference level of the reference channel, the sensor initial cavity length is chosen between 25μm to 30μm where the interference fringe visibility of the reference channel is below 1%. The system performance can also be improved by correcting the dark current induced bias which is a concern when the power level of the system becomes very low in case of long distance operation. Finally, the optical neutral density filter is used in the reference channel to balance the optical power of the two channels so that the same amplifying circuit can be used for both channels to minimize the non-linear effects from the amplifiers.

Comprehensive experiments are performed to systematically evaluate the performance of the instrumentation, the sensor probes and the sensor systems. The major test results are summarized in Table 8-1 through Table 8-3, which give us the confidence to believe that the development of the fiber optic SCIIB pressure sensor system provides a reliable tool for the pressure measurement capable of operating in high pressure, high temperature harsh environments.

Table 8-1. Summary of the test results for SCIIB instrumentation

Test items	Test results
Self-compensation for optical power variations	<0.3% up to 50% loss
Polarization dependence	<0.5%
Dynamic error	<0.027% (20°C to 57°C)

Table 8-2. Summary of the test results for SCIIB sensor probe

Test items	Test results
Survivability of the sensor probe in high pressure and high temperature environments	Excellent (>98%)
Sensor annealing	600°C for 24 hours
Temperature sensitivity of multimode sensor (Gauge length: 0.7mm, initial cavity length of 5.160μm)	2.7×10^{-7} /°C
Temperature sensitivity of multimode sensor (Gauge length: 0.7mm, initial cavity length of 25.460μm)	2.87×10^{-8} /°C

Table 8-3. Summary of the performance evaluation results for SCIIB sensor system

Test items	Test results
Nonlinearity	<0.1%
Hysteresis	Not noticeable
Resolution	0.003% (2σ)
Repeatability	Better than 0.15%
System stability	<0.04% variation in 24 hours
Temperature cross-sensitivity	0.04% /°C
Overpressure effects	Not noticeable

8.2 Outline of Future Work

Based on the development work done so far, some future work is suggested to further enhance the robustness and reliability of the SCIIB pressure sensor systems to achieve the final goal of capable of conducting accurate pressure measurements in practical downhole applications. The further investigation is suggested to cover the following aspects.

1. Sensor protection

For a long-term reliable measurement, the SCIIB sensor probe needs to be well protected against water penetration. Research work should be conducted to investigate different protection methods to block the diffusion of water molecules into the capillary tube and the fibers, at the same time without adverse effects on the sensor performance.

2. Further reduction of the temperature cross sensitivity

The reduction of the temperature cross sensitivity should be investigated from both the sensor side and the system side. Using a more accurate measurement method, the precise temperature dependence of the sensor probe can be measured to reveal an optimal geometric design of the sensor probe to achieve zero temperature cross sensitivity. Reduction of the sensor's temperature dependence should also be further investigated through the optimal choice of the capillary tube used for the sensor fabrication. The change of the spectrum characteristics of the optical bandpass filter contributes a significant amount of dynamic error to the sensor system. Therefore, future investigation should be conducted to find a filter with more stable spectrum characteristics.

3. Further reduction of the polarization dependence

The use of the fiber optic depolarizer has shown dramatic reduction of the polarization dependence of the sensor system. However, it is necessary to find a depolarizer with a spectral width no less than that (10nm) of the optical bandpass filter used in the signal channel.

4. Improvement of the signal processing in digital domain

The performance of the SCIIB sensor system can be further improved with filtering techniques in the digital domain by the host computer. Digital filters can be implemented to further reduce the high frequency noise from the output of the SCIIB two channels before the ratio function is performed.

5. Field evaluation

A complete field test of the system is necessary to comprehensively evaluate the overall performance of the SCIIB sensor system. The field test results should also serve well to further optimize the sensor and system design for the successful commercialization of the SCIIB sensing technology.