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Optical Fiber Sensor Technologies for Efficient and Economical Oil Recovery

Project Evaluation Report

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1.0 Executive Summary

This report summarizes technical progress over the first ten months of the second year of the Optical Fiber Sensor Technologies for Efficient and Economical Oil Recovery program, funded by the Federal Energy Technology Center of the U.S. Department of Energy, and performed by the Photonics Laboratory of the Bradley Department of Electrical and Computer Engineering at Virginia Tech. The main objective for this three and one-half year program is the development and demonstration of cost-effective, reliable optical fiber sensors for the measurement of temperature, pressure, flow, and acoustic waves in downhole environments for use in oil recovery.

The sensors being developed under this program are based on the Self-Calibrated Interferometric/Intensity-Based (SCIIB) fiber optic sensor configuration invented at the Photonics Laboratory. The SCIIB design measures displacement (elongation or contraction) of a small Fabry-Perot interferometer cavity constructed in an optical fiber. The Fabry-Perot assembly is typically cylindrical, and generally has dimensions on the order of 0.1 mm in diameter and 5 mm long. By proper mechanical design of the assembly, physical parameters such as pressure, temperature, and flow can be made to induce a displacement in the Fabry-Perot assembly, which may then be measured by the SCIIB system. In the SCIIB design, the Fabry-Perot assembly is designed so that the output of the cavity over the sensor's dynamic range is limited to remain in the quasi-linear region of the interference signal output by the cavity. In this way, interpretation of the nonlinear output of typical interferometers is avoided, simplifying the signal processing.

The SCIIB system uses optical filtering to process the optical signal output by the Fabry-Perot cavity so that two signals are produced: one which contains information about the cavity displacement, and another that contains information regarding undesired effects in the first signal, such as fluctuations in the optical source power, or changes in optical fiber loss. The second signal is used as a reference to eliminate these undesired effects, and provide self-calibration functions in the sensor.

During the reporting period (1 Oct 99 to 15 Aug 00), research efforts under the program were directed towards improvement of the processes for fabricating SCIIB sensors, improvement and evaluation of the performance of the SCIIB opto-electronic signal conditioning system, and development and testing of strategies for the protection of optical fibers and sensors in the downhole environment. The research progress is summarized in this section, and is described in detail in the main body of the report.

The operating principles of the SCIIB technology were further studied through detailed analysis. Based on a comprehensive mathematical model of the SCIIB opto-electronic signal conditioning, simulations were conducted to provide important guidelines for the improved system design.

Three SCIIB opto-electronic signal conditioning systems were designed and built. The performance of the systems was tested, and found to be superior to that of previous systems demonstrated in the first year of the program. The low-cost multimode SCIIB

system, operated at 850nm wavelength, is a good solution for short distance applications, where the relatively large fiber attenuation is not a concern. The two single-mode fiber-based SCIIB systems, operating at 1310nm wavelength, are better suited for applications where the opto-electronic system must be remotely located several kilometers from the sensor.

A detailed system noise analysis was also conducted 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 random changes in the state of polarization of light propagating in the fiber is the dominant source of error. The optical noise analysis also indicated that temperature-induced change of the spectral characteristics of the optical bandpass filter contributes the most to the dynamic error of the system. Drift of the source spectrum and spectrum shifts induced by fiber bending will only affect the system performance slightly through non-centered filtering and residual interference of the reference channel.

Based on the system noise analysis results, strategies to enhance the opto-electronic system performance were evaluated. The polarization error was reduced significantly by adding a depolarizer to the system. By matching the optical filter center wavelength to the center of the light source spectrum, the measurement error resulting from non-centered filtering was also reduced dramatically. To achieve a compromise between the filter spectrum shift effect and residual interference level of the reference channel, the sensor initial cavity length was chosen to be between 25 μ m to 30 μ m, where the interference fringe visibility of the reference channel was negligible. The system performance was also improved by correcting the dark current induced bias, which was very important to assure the system performance for long distance operations. Finally, an optical neutral density filter was used in the reference channel to balance the optical power of the two channels so that the same amplifying circuit could be used for both channels, to minimize non-linear effects from the amplifiers.

Comprehensive experiments were conducted to evaluate the performance characteristics of the developed opto-electronic SCIIB signal processing units. The tests of the self-compensation capability indicated that the developed SCIIB signal processing units can maintain their accuracy of 0.3% even when the optical power loss was as high as 50%. The test results revealed that the polarization dependence of the developed signal processing units is less than one percent. By testing the signal processing units in an electrical oven, the dynamic error of the systems was found to be less than 0.027% per °C over a temperature change from 20°C to 57°C.

The sensor fabrication system, which is based on controlled thermal bonding of the sensor elements, was 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 repeatability of sensor fabrication has been improved dramatically by the development of centroid and peak/valley tracking algorithms for the on-line real-time sensor cavity length monitoring system, and by

adding a high-resolution piezoelectric stage to the micropositioning system. The initial sensor cavity length can now be controlled precisely to desired operating point with an accuracy of 2 nm. Also, by adding a mirror set to the sensor fabrication system, the mechanical strength of the fabricated sensor was further improved through more uniform irradiation of the sensor assembly by the CO₂ laser.

Comprehensive evaluations were also conducted for both multimode and single-mode fiber SCIIB sensor probes. Over one hundred sensors were fabricated and tested, and over 98% of these sensors survived the tests in high pressure and high temperature environments. Experiments results also revealed that annealing the sensors at 600°C for 24 hours significantly improves the stability of SCIIB sensors. The temperature sensitivity of multimode fiber based pressure sensor probes was found to be 2.7×10^{-7} per °C, and that of the single-mode fiber based sensor probes was tested to be as low as 2.87×10^{-8} per °C.

Comprehensive experiments were performed to systematically evaluate the performance of the SCIIB sensor systems. The performance characteristics that have been evaluated so far include linearity, hysteresis, resolution, repeatability, system stability, temperature cross sensitivity, over pressure capability, and long distance sensor addressing capability. The test results, as summarized in Table 1-1, give us the confidence to believe that the development of the fiber optic SCIIB sensor system can provide a reliable measurement tool for various downhole applications.

Test items	Test results
Nonlinearity	<0.1%
Hysteresis	Not measurable
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 measurable
Long distance sensor addressing	No noticeable performance degradations over the distance of 12.7km

Table 1-1. Summary of the performance evaluation results for SCIIB sensor system

- In the use of optical fiber sensors in down-hole environments in the oil exploration and recovery industry, it will be necessary for the fiber to bend around narrow passages and be subjected to both high temperatures (up to about 200°C) and high pressures (up to 20,000 psi). Testing of the minimum bend radius that the fiber can sustain without fracture has been completed to test the radius at failure for uncoated and polyacrylate coated single-mode optical fibers exposed to 200°C for up to 30 days. The results show that uncoated fibers have a larger minimum bend radius than coated fibers, while both coated and uncoated fibers exposed to 200°C exhibit a larger minimum bend radius than as-received fiber. Since glass materials in general are susceptible to stress corrosion cracking

(where the bend radius at failure depends upon the time for which the fiber is held at a given radius) time to failure studies at fixed bend diameters were undertaken.

- The downhole environment presents a particular hazard for glass optical fibers, due to the existence of water in most well bores, and to the role of water in stress corrosion. Water dramatically accelerates the rate of failure due to stress corrosion in glass, by chemically breaking silica macromolecules, thereby weakening the glass network. In anticipation of the need to protect the optical fibers from moisture penetration through the use of protective hermetic coatings, a theoretical analysis was undertaken to calculate the minimum bend diameter versus coating thickness for a range of materials. In general, the thickness of the coatings are required to be less than about 100 microns (using a failure criterion set at 0.002 plastic strain) for the materials studied.
- An apparatus was constructed to test the penetration rate of water into the optical fiber at 300°C and 1441 psi pressure. A carbon/polyimide-coated fiber, a polyacrylate-coated fiber inserted inside a stainless steel (hypodermic needle) tube, and a normal polyacrylate-coated fiber were tested simultaneously. White light was injected into the one end of each of the fibers under test, and a spectrometer was used at the output end of the fibers to monitor the absorption spectra. The absorption due to the hydroxyl group (which is a reliable gauge of water penetration) has been monitored for approximately the last six months. In the normal polyacrylate coated optical fiber, the loss due to absorption of water is very large. In comparison, however, the optical loss due to absorption of water in the carbon/polyimide coated fiber is very small. The fiber in the stainless steel tubing has shown no detectable penetration of water as measured by the optical absorption losses. The rate of diffusion of water into the fiber is exponentially dependent upon the temperature and since the testing conditions represent much higher temperatures than expected during actual service, the lifetimes for the carbon/polyimide coated and the stainless steel needle tubing at 200°C are expected to be very long. The data clearly show that the carbon/polyimide coated and the stainless steel tubing approaches can provide excellent protection against water penetration.
- In order to ensure that the sensor systems developed will have a suitable lifetime under these conditions, experimental apparatus and procedures have been setup to simulate the high temperature, high pressure down-hole environment. Testing the response of polyacrylate-coated pressure sensors at temperatures up to 200°C and at pressures up to 8,000 psi for periods of time up to 30 days in water has been completed. The test results show a shift in the measured pressure as a function of time, which is suspected to be caused by the penetration of water into the glass tubing material. Based on the outstanding results of the fiber protection testing, metal and carbon coatings are being investigated for protection of the sensor head as well, in order to minimize water-induced shifts in the sensor response. Gold-coated sensors have been produced by sputtering techniques. Results from the

gold-coated sensors to date have shown that the gold coating does not provide adequate protection to the sensor head. Carbon-coated sensors are being investigated as well. Amorphous carbon has been deposited using laser ablation deposition techniques. The deposition system uses a krypton-fluoride pulsed excimer laser to deliver the energy density required to ablate the carbon target in a vacuum chamber. Analysis of the coating quality and uniformity of these coatings has been performed by optical microscopy and scanning electron microscopy. The coatings appear to be very uniform in thickness and distribution. Experiments have been successfully performed to overcoat the carbon with a polyimide coating to protect the carbon coating from abrasion. The sensors are currently undergoing long term evaluation of the high temperature, high pressure performance in water to evaluate sensor repeatability for pressure measurements.

2.0 Principle of SCIIB Sensor Operation

The self-calibrated interferometric/intensity-based (SCIIB) fiber optic sensor successfully combines the advantages of both the interferometric and the intensity-based fiber sensors in a single system. Through a proper design of the sensor, the SCIIB technology can provide absolute measurement of various parameters with the full self-compensation capability for the source power fluctuation and the fiber loss changes. Starting with a review of fiber optic Fabry-Perot sensing techniques, this chapter will present the configuration of the SCIIB system followed by the detailed discussion of the unique signal processing method that offers the system self-calibration capability.

2.1. SCIIB System Configuration

The basic configuration of the SCIIB fiber sensor system can be illustrated using Figure 2.1. The system includes a sensor probe, a broadband source, an optoelectronic signal processing unit and silica glass fibers linking the sensor probe and the signal-processing unit.

The light from the broadband optical source (for example an LED) is launched into a two-by-two fiber coupler through the pigtailed fiber, and propagates along the optical fiber to the sensor head. The sensor head is constructed by inserting two optical fibers, with their endfaces cleaved, into a capillary tube so that an air-gapped low finesse Fabry-Perot cavity is formed between the two fiber endfaces, as shown in the enlarged view of the sensor head. The incident light is first partially reflected ($\sim 4\%$) at the endface of the input fiber. The remainder of the light propagates across the air gap to the endface of the reflector fiber, where a second reflection ($\sim 4\%$) is generated. The two reflections then travel back along the same fiber and through the same fiber coupler to the signal-processing unit. The signal processing part of the SCIIB system extracts the information about the Fabry-Perot cavity length, which is related to various measurands governed by different physical laws.

Figure 2.1. Illustration of the principle of SCIIB fiber optic sensor system

2.2 SCIIB Signal Processing

From the theories of optics, we know that the coherence length of a source is inversely proportional to the spectral width of the source. The coherence length L_c can be estimated by the following formula

$$L_c \approx \frac{\lambda_c^2}{\Delta\lambda}, \quad (1)$$

where λ_c is the central wavelength of the source and $\Delta\lambda$ is the spectral width of the source. To obtain an interference signal from the interferometer, the optical path difference (OPD) has to be smaller than the coherence length of the source. If the OPD of the interferometer is larger than the coherence length of the source being used, the two optical waves will not effectively interfere to generate fringes.

As shown in Figure 2.1, the reflected light from the sensor head is split into two channels with different optical properties through optical filtering. The light in Channel 1 remains its original spectral width (broadband spectrum) while the light in Channel 2 has a narrower spectrum by passing it through an optical bandpass filter. The different spectral widths of the light result in different coherence lengths of these two channels.

Let's study the two channels output signals in terms of optical interference. First, Let's assume that the original spectrum width of the source can be approximated as a Gaussian profile with a spectral width of $\Delta\lambda_1$, and also assume that the spectral characteristic of the optical bandpass filter is a Gaussian profile too, but with a different spectral width of $\Delta\lambda_2$. The light spectra seen by the two SCIIB channels can thus be expressed by

$$I_{s1,s2}(\lambda) = \frac{2I_{10,20}}{\sqrt{\pi}\Delta\lambda_{1,2}} \exp\left(-\frac{(\lambda - \lambda_c)^2}{\Delta\lambda_{1,2}^2}\right), \quad (2)$$

where $I_{10,20}$ are the optical powers of the two channels respectively, and λ_c is the central wavelength for both channels (here, we assume that the two channels have the same central wavelength).

The interference signals resulting from the spectra of the two channels can thus be written as

$$I_{1,2} = R \cdot \int_{-\infty}^{\infty} I_{s1,s2}(\lambda) [1 + \eta^2(1-R)^2 - 2\eta(1-R)\cos(\frac{4\pi}{\lambda}L)] d\lambda, \quad (3)$$

where

$I_{s1,s2}$ are the spectral power density distribution of the two channels respectively,
 R is the reflectance at the boundary of the air and the fiber endface,
 L is the cavity length, and
 η is the coupling coefficient of the Fabry-Perot cavity. It is a function of the cavity length L , the lateral offset, and the angular offset. Because the initial cavity length usually is chosen to be very small, the optical loss of the cavity is very small. Therefore, η can be approximated as 100%.

The reflectance R can be calculated by

$$R = \left[\frac{(n - n')}{(n + n')} \right]^2, \quad (4)$$

where n is the refractive index of the fiber core, and n' is the refractive of the medium forming the cavity between two fibers, which in our case is the air. The reflectance at the fiber endfaces is thus about 4% of the total incident optical power.

Notice that since the reflectance is relatively small, the interference signals given by Equation (3) can thus be approximated by

$$I_{1,2} \approx 2R \cdot \int_0^\infty I_{s1,s2}(\lambda) \left[1 - \cos\left(\frac{4\pi}{\lambda} L\right) \right] d\lambda. \quad (5)$$

Equation (5) indicates that the interference signal is the superposition of interference contribution of all the spectral components. Here we have assumed that the photodetectors have a flat response over the source emission spectrum.

By taking the ratio of the two channels outputs, we then have the SCIIB output given by

$$s = \frac{I_2}{I_1} \approx \frac{\int_{-\infty}^{\infty} I_{s2}(\lambda) \left[1 - \cos\left(\frac{4\pi}{\lambda} L\right) \right] d\lambda}{\int_{-\infty}^{\infty} I_{s1}(\lambda) \left[1 - \cos\left(\frac{4\pi}{\lambda} L\right) \right] d\lambda}. \quad (6)$$

Figure 2.2 shows the output signals from the two SCIIB channels, and Figure 2.3 plots their ratio given by Equation (6) as the function of the sensor cavity length, where the source spectral width is assumed to be 40nm and that of the bandpass filter is 10nm, which corresponds to the single-mode fiber sensor case as we will discussed later. Figure 2.4 and Figure 2.5 show the similar simulation results for the case in accordance with the multimode fiber sensor system which uses a source with the spectral width of 70nm and the spectral width of the filter is 10nm.

Figure 2.2. Interference fringes of the SCIIB two channels, where the source has the spectral width of 40nm and the central wavelength of 1310nm; the spectral width of the bandpass filter is 10nm, in accordance with the single-mode fiber sensor system.

Figure 2.3. Ratio of the two channels' outputs of Figure 2

If we fabricate the sensor probe in such a way that it has an initial cavity length that is larger than the coherence length of Channel 1 but smaller than the coherence length of Channel 2, then, as shown in Figure 2.2 and 2.3, Channel 1 becomes an intensity channel with its output relatively unchanged, while Channel 2 remains its highly visible interference fringes as the cavity length changes.

Figure 2.4. Interference fringes of the SCIIB two channels, where the source has the spectral width of 70nm and the central wavelength of 850nm; the spectral width of the bandpass filter is 10nm, in accordance with the multimode fiber sensor system.

Figure 2.5. Ratio of the two channels' outputs of Figure 4

The output from Channel 1 (non-interference channel) and Channel 2 (interference channel) of the SCIIB sensor can now be expressed as

$$I_1 \approx 2RI_{10} \quad (7)$$

and

$$I_2 = 2R \cdot I_{10} \cdot \alpha \cdot [1 - \gamma \cos(\frac{4\pi}{\lambda} L)], \quad (8)$$

where, α is the power loss of the optical filter in Channel 2, given by

$$\alpha = \frac{I_{20}}{I_{10}}, \quad (9)$$

and γ is the fringe visibility of Channel2's signal, which is defined by

$$\gamma = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}, \quad (10)$$

where, $I_{\max}$ and $I_{\min}$ is the maximum and minimum intensity of the optical interference respectively. The fringe visibility in our case is a function of η , R , and $\Delta\lambda_2$.

In principle, continuously tracking the phase change of the interference fringes in Channel 2 would permit measurement of the change of the cavity length of the sensor head. Like the output of a regular interferometer, the measurement will have ultra-high sensitivity. One period of fringe variation corresponds to an air gap change of one-half of the optical wavelength. However, the fiber loss variations and the laser power drift could introduce errors to the amplitude of the interference signal and result in a poor accuracy of the measurement. To avoid these two adverse effects, we introduce the output from Channel 1 to the signal processing as a reference signal, and the SCIIB sensor output is evaluated as the ratio of the two signals of the two channels, given by

$$\begin{aligned} s = \frac{I_2}{I_1} &\approx \frac{2RI_{10}\alpha[1 - \gamma \cos(\frac{4\pi}{\lambda} L)]}{2RI_{10}} \\ &= \alpha[1 - \gamma \cos(\frac{4\pi}{\lambda} L)] \end{aligned} \quad (11)$$

The two channel signals are from the same source and experience the same transmission paths. They thus have similar behaviors in terms of source power fluctuation and fiber loss variations. As indicated in Equation (11), the ratio of the outputs from Channel 2 and Channel 1 is only a function of the Fabry-Perot cavity length, which can thus eliminate these two sources of errors from the final result of the measurement.

To assure the proper self-referencing function of the SCIIB sensor system, it is very important to choose an optimal initial sensor cavity length that gives the signal channel maximum fringe visibility and at the same time the interference of the reference channel is suppressed to minimum. The choice of the optimal initial cavity length will mainly depend on the spectral widths of the two SCIIB channels. For example, in the case shown in Figures 2.2 and 2.3, the initial cavity length can be chosen between 20 and 30 μ m. On the other hand, for the case shown in Figure 2.4 and 2.5, the initial cavity length can be somewhere from 7 to 12 μ m. However, there are other considerations in determining an optimal initial cavity length, which will be further studied later.

2.3 Linear Operating Range of SCIIB Sensor

Regular interferometric sensors suffer from the disadvantages of sensitivity reduction and the fringe direction ambiguity when the sensor output reaches the peak or valley of an interference fringe. Sensitivity is reduced at the peak or valley of a fringe since at that point the change in optical intensity is zero for a small change in the sensor cavity length. Fringe direction ambiguity refers to the difficulty in determining from the optical intensity whether the sensor cavity is increasing or decreasing. To avoid these two problems, we design and fabricate the SCIIB sensor head to operate only over the semi-linear range of a half fringe, as shown in Figure 2.6, so that a one-to-one quantitative relation between output intensity and the sensor cavity length is obtained.

Figure 2.6. Illustration of a semi-linear operating range of fringes.

We define the linear range of the SCIIB sensor based on the change of its sensitivity. From Equation (11), the sensitivity of the SCIIB sensor can be calculated by

$$\text{Sensitivity} = \text{abs}\left(\frac{ds}{dL}\right) = \text{abs}\left(\alpha\gamma \frac{4\pi}{\lambda} \sin\left(\frac{4\pi}{\lambda} L\right)\right). \quad (12)$$

The maximum sensitivity is obtained at the Quadrature (Q)-points of the interference fringes, which is

$$\text{Maximum Sensitivity} = \alpha\gamma \frac{4\pi}{\lambda}. \quad (13)$$

Correspondingly, we define the operating range of the SCIIB sensor as its sensitivity remaining within the 60% of the maximum sensitivity. Therefore the operating range can be calculated by

$$\{\text{Operating Range}\} = \text{Solution}\left\{\text{abs}\left(\alpha\gamma \frac{4\pi}{\lambda} \sin\left(\frac{4\pi}{\lambda} L\right)\right) \leq \gamma \frac{4\pi}{\lambda} \cdot 60\%\right\}, \quad (14)$$

which results in the maximum change of the signal level Δs given by

$$\Delta s_{\max} = 1.6\alpha\gamma. \quad (15)$$

2.3 Major Advantages of the SCIIB Sensor Technology

In addition to the generic fiber sensor advantages such as small size, lightweight, remote operation, immunity to EMI, electrically non-conducting, and chemical inertia, the unique SCIIB signal processing method combines the advantages of both interferometric and intensity-based sensors and provides the sensor a number of other major advantages as summarized as below:

Ultra-high sensitivity.

The SCIIB fiber optic sensor can offer a very high resolution to the measurement since the essence of the signal processing is based on interferometry.

Absolute measurement.

The operating range of the SCIIB sensor is limited to the semi-linear range of half of an interference fringe; therefore the sensor output is a unique and almost linear function of the change of the cavity length. The one-to-one relation between the sensor output and the cavity length makes it possible to measure the absolute value of the sensor cavity length after the initial cavity length is chosen and fixed. Not only the direction ambiguity problem is solved, but also the sensitivity of the sensor is kept relatively constant during the entire operating range.

Minimized complexity in signal processing.

Because the signal processing of the SCIIB sensor only involves optical power detection and a simple ratio operation of the two output signals, the complexity of the system is then kept to its minimum level.

Self-compensation capability.

Since the original broadband source spectrum is used as a reference signal, the drift of source power and fluctuations in fiber attenuation are thus fully compensated by the SCIIB signal processing.

High frequency response.

Because the very simple signal processing is used, the SCIIB sensor potentially has a very high frequency response, which may allow to detect very high-speed signals such as acoustic waves or aerodynamic forces.

Geometric flexibility.

The Fabry-Perot sensor head structure can also offer a great design flexibility to accommodate the requirements for different applications.

3.0 Design and Implementation of the SCIIB Sensor Systems

This section will describe the design and implementation of two SCIIB sensor systems. One system is multimode fiber-based at a low cost used for short distance applications. The other is a single-mode sensor system designed for long distance applications.

3.1 Multimode Fiber-Based SCIIB System

Multimode fibers have a large core diameter. Therefore, optical power can be coupled from the source into the fiber efficiently and cheaply. However, because of the relatively high loss of the multimode fiber at this wavelength, the system is mainly designed for short distance applications at a low cost, typically less than 1km from the actual sensing region to the signal processing unit.

The multimode fiber-based SCIIB sensor system, with its schematic design shown in Figure 3.1, and the photo of the system shown in Figure 3.2, is designed to operate at the central wavelength of 850 nm and uses 62.5 μ m/125 μ m standard telecommunication fibers.

The source used for the multimode SCIIB system is an LED (Honeywell, HEF 4854-014). The spectrum of the LED is given in Figure 3.3, with its central wavelength of 850 nm, spectral width of 70 nm, and the typical output power of 120 μ W to a 62.5/125 μ m multimode fiber. In the multimode fiber system, a polarization insensitive cubic beam splitter with the splitting ratio of 50:50 is used to split the light from the sensor head into two channels. One portion of the light from the beam splitter passes an optical bandpass filter with the central wavelength of 850 nm and the full width at the half maximum (FWHM) of 10 nm. Two silicon detectors with larger effective areas (31 mm²) are used to receive the signals of the channels. After amplified using two trans-impedance amplifiers, the two signals from these two channels are sampled and converted to digital data by a high-precision A/D converter. The ratio function of these two channel signals is then performed by a host computer.

3.2 Self-Compensation Capability Test for the Multimode SCIIB System

One unique advantage of the SCIIB sensor is its capability of self-compensation for fiber loss variation or source power drifting. The SCIIB sensor uses two channels with different coherent lengths for sensing and referencing respectively. The self-compensation results from the fact that the optical power received at these two channels comes from the same source and experiences the same transmission path. The common unwanted effects can therefore be eliminated by taking the ratio of the two output signals of the two channels.

Figure 3.1. Schematic of the multimode SCIIB sensor system

Figure 3.2. Photograph of the developed multimode fiber-based SCIIB sensor system

Figure 3.3. Optical spectrum of the source LED

Figure 3.4 shows preliminary test results of the fiber loss compensation capability of the multimode fiber-based SCIIB system. The fiber used in the test was a standard telecom 62.5/125 μm graded index multimode fiber. We introduced power loss to the system by manually bending the fiber to various diameters without changing the sensor cavity length. Two multimeters were used to record the output voltages from each channel. As expected, although the outputs of the two channels changed due to the increase of the power loss, the ratio of the two channel outputs remained the same. The sensor output ratio varied less than 1% over the full testing range (up to 50% of the total power loss), which indicated that the implemented multimode fiber-based SCIIB system had an excellent self-calibration capability to compensate the fiber loss variation.

Figure 3.4. SCIIB sensor output compensated for fiber bending loss.

3.3 Single-Mode Fiber-Based SCIIB System

Single-mode fibers have very low optical attenuation to the transmitted light. The typical attenuation of single-mode fiber is about 0.3dB/km at the wavelength of 1300nm and 0.2dB/km at the wavelength of 1550nm. Therefore, light can be transmitted inside the single-mode fiber for a very long distance. However, due to the small core diameter of single-mode fibers, it is relatively difficult to couple the light efficiently from optical sources into the fiber. Also, the low-noise detection of the light at 1300nm or 1550nm requires expensive InGaAs photodetectors. Therefore, the cost of single-mode fiber-based sensor systems is much higher compared to those made by multimode fibers. The single-mode fiber-based SCIIB sensor system is mainly designed for long distance applications, typically longer than one kilometer from the actual sensing region to the signal processing unit.

Figure 3.5. Schematic of the single-mode SCIIB sensor system

The schematic of the single-mode SCIIB sensor system is shown in Figure 3.5, and the photograph of the system is shown in Figure 3.6. The single-mode SCIIB system is designed to operate at the central wavelength of 1310 nm and to use single-mode fiber to transmit optical signals between the sensor probe and the signal-processing unit.

Figure 3.6. Photograph of the developed single-mode SCIIB sensor system

The source used for the single-mode fiber-based SCIIB system is a high power superluminescent light emitting diode (SLED) provided by Anritsu Corp. (AS3B281FX), with the central wavelength of 1312 nm, the spectral width of 41.5 nm, and the output power of 1.21mW from a 9/125 μ m pigtailed single-mode fiber. Figure 3.7 shows the source spectrum measured by an Ando Optical Spectrum Analyzer (OSA).

Figure 3.7. Optical spectrum of the SLED source

A polarization insensitive beam splitter with a splitting ratio of 50:50 at the wavelength of 1310nm is used to split the light signal from the sensor head into two channels. At one channel, the light passes an optical neutral density filter (its function will be discussed in Chapter 5) and is detected by a larger effective area InGaAs photo-detector and amplified to offer the reference signal. The light in the other channel passes through an optical bandpass filter with its central wavelength at 1310 nm and the FWHM spectral width of 10 nm. Because the spectral width of this channel is much narrower, an interferometric signal as the function of the sensor cavity length can thus be obtained after the photo-detection. Similar to the multimode fiber-based system, the two channels' outputs are sampled and converted to digital signals and input to a host computer where the ratio and linearization can be performed easily.

3.4 Electronic Circuits and Software

The receiving electronics for the photodetectors are very simple, employing a transimpedance amplifier to convert the photocurrent from the photodetector to a voltage output. The schematic of the circuit is shown in Figure 3.8. The central unit is a low noise FET operational amplifier (AD795) manufactured by the Analog Device Corp. The circuit is designed to have a voltage-current gain of 10^7 V/A and the 3dB bandwidth can be calculated as:

$$f_{3dB} = \frac{1}{2\pi R_1 C_1} = 15.92 \text{ (Hz)} \quad (16)$$

SCIIB signal processing requires a ratio function to compensate the unwanted optical power fluctuation. In the system implementation, the ratio of the two channels is performed digitally through the host computer. A 23-bit data acquisition system purchased from Lawson Labs Inc. was used in the system to convert the analog output from the SCIIB two channels to digital data.

Figure 3.8. Schematic of the receiving electronic circuit

($R_1 = R_2 = 10 \text{ M}\Omega$, $C_1 = C_2 = 1000 \text{ pF}$)

Computer programs were also written to interface the A/D system so that two channels were sampled alternatively. A scanning window filter was designed in the software to further filter the high frequency noise. After the dark current correction, the ratio of the two channels data was mapped to pressure output through the prestored calibration curve.

4.0. SCIIB System Noise Analysis

As an optoelectronic measurement system, the performance of the SCIIB sensor is limited by the noises associated with each individual electronic and optical component and their combined effects. A detailed analysis of these noise effects on the system performance is a very important design step since it provides a guideline to achieve an optimal system performance. This section provides a detailed analysis of the noise performance of the single-mode fiber (SMF) SCIIB sensor system, including both the electronic noise and the optical noise. Based on the analysis results, performance improvement measures are proposed.

4.1 Electronic Noise of the SMF SCIIB System

Usually, the ultimate limit of the performance of an optoelectronic sensor system is associated with the receiving electronics used to interrogate the sensor. This can be further decomposed into two parts: 1) the fundamental photon noise limit (shot noise) of the photodetector, and 2) thermal noise of the electronics. In addition to the noise associated with the receiving electronics, the noise of the optical source, such as the optical power fluctuation and the source wavelength drift, can also cause measurement errors to the sensor system. Here the optical power fluctuation of the source is no longer a concern because as previously discussed in Section 1 the SCIIB sensor system can self-compensate for the source power fluctuation. The error caused by the optical wavelength drift of the source will be discussed in the next section as it is categorized to be part of the optical noise. Therefore this section will be devoted to the discussion of the electronic noise only.

4.1.1 Photodetector Noises

4.1.1.1. Shot noise

Shot noise of a photodetector is a manifestation of the fact that the electric current consists of a stream of electrons that are generated at random times. It was first studied by Schottky in 1918 and has been thoroughly investigated since then [1]. The photodiode current generated in response to a constant optical signal can be written as

$$I(t) = I_p + i_s(t), \quad (17)$$

where $I_p = RP_{in}$ is the average current and $i_s(t)$ is a current fluctuation related to shot noise. P_{in} is the input optical power to the photodetector and R is the responsivity of the photodetector.

Mathematically, $i_s(t)$ is a stationary random process with Poisson statistics which in practice can be approximated by the Gaussian statistics. The autocorrelation function of $i_s(t)$ is related to the spectral density $S_s(f)$ by the Wiener-Khinchin theorem

$$\langle i_s(t) i_s(t + \tau) \rangle = \int_{-\infty}^{\infty} S_s(f) \exp(2\pi i f \tau) df. \quad (18)$$

The spectral density of shot noise is constant and is given by $S_s(f) = qI_p$ (shot noise is called white for this reason). q is the charge on an electron (1.6×10^{-19} C). Note that $S_s(f)$ is a two-sided spectral density, as negative frequencies are also included in Equation (18). If only positive frequencies are considered by changing the lower limit of integration to zero, the one-sided spectral density becomes $2qI_p$.

The noise variance is obtained by setting $\tau=0$ in Equation (18) and is given by

$$\sigma_s^2 = \langle i_s^2(t) \rangle = 2qI_p \Delta f, \quad (19)$$

where Δf is the effective noise bandwidth of the receiver. The actual value of Δf depends on where the noise is measured and it usually corresponds to the bandwidth of the amplifying circuits.

4.1.1.2. Dark current

All photodetectors generate some current noise even in the absence of an optical signal because of stray light or thermal generation of electron-hole pairs. This residual current is referred to as the dark current. Since the dark current I_d also generates shot noise, its contribution is included in the following equation

$$\sigma_s^2 = 2q(I_p + I_d) \Delta f. \quad (20)$$

4.1.1.3. Thermal noise

At a finite temperature, electrons in any conductor move randomly. Random thermal motion of electrons in a resistor manifests as a fluctuating current even in the absence of an applied voltage. The load resistor in the front end of an optical receiver adds such fluctuations to the current generated by the photodiode. This additional noise component is referred to as thermal noise. It is also called Johnson noise or Nyquist noise after the two scientists who first studied it experimentally and theoretically. Thermal noise can be defined as the current fluctuation $i_T(t)$. Mathematically, $i_T(t)$ is modeled as a stationary Gaussian random process with a spectral density that is frequency independent up to 1 Thz (nearly white noise) and is given by [2]

$$S_T(f) = \frac{2k_B T}{R_L}, \quad (21)$$

where k_B is the Boltzmann constant ($1.38 \times 10^{-23} \text{ J/K}$), T is the absolute temperature, and R_L is the load resistor. As mentioned before, $S_I(f)$ is also the two-sided spectral density.

The autocorrelation function of $i_T(t)$ is given by

$$\langle i_T(t) i_T(t + \tau) \rangle = \int_{-\infty}^{\infty} S_I(f) \exp(2\pi i f \tau) df \quad (22)$$

Therefore, the noise variance is obtained by setting $\tau=0$ and becomes

$$\sigma_s^2 = \langle i_s^2(t) \rangle = \int_{-\infty}^{\infty} S_I(f) df = \frac{4k_B T}{R_L} \Delta f \quad (23)$$

where Δf is the effective noise bandwidth which is defined same as for the shot noise case.

4.1.2 Noise assumption at the transimpedance amplifier

The developed SCIB system uses two transimpedance amplifiers to convert the optical current signals to the voltage outputs of the two channels. It is thus worthwhile to describe the noise performance of the transimpedance amplifier as it converges the shot noise and the thermal noise, and also introduce other noises to the final sensor output.

The noise equivalent circuit of the transimpedance amplifier (as shown in Figure 14) is given in Figure 4-1. The bandwidth of the transimpedance amplifier is RC limit and given by

$$\Delta f = \frac{1}{2\pi R_f C_f}, \quad (24)$$

where R_f is the feedback resistance, and C_f is the feedback capacitance.

The output voltage (e_o) from the transimpedance amplifier can be calculated by

$$e_o = e_s + e_{no} = I_p R_f + e_{no}, \quad (25)$$

where e_s is the signal voltage of the amplifier, I_p is the signal generated photocurrent from the photodetector, and e_{no} is the voltage noise of the amplifier which includes the shot noise of the detector generated a noise voltage, the thermal noise of the feedback resistor (e_{noR}), the amplifier's input current noise (e_{noi}), and the amplifier's input voltage noise (e_{noe}).

Figure 4-1. Noise equivalent circuit of the transimpedance amplifier

4.1.2.1. Effect of the photodetector shot noise

The shot noise generated at the photodetector (i_s) will be amplified by the feedback resistor and gives the corresponding voltage noise (e_{nos}) given by

$$e_{nos} = i_s R_f = \sqrt{2q(I_p + I_d)\Delta f} R_f, \quad (26)$$

4.1.2.2. Thermal noise of the feedback resistor

The thermal noise of the feedback resistor generates a voltage noise e_{noR} that can be expressed by

$$e_{noR} = \sqrt{4k_B T R_f \Delta f}, \quad (27)$$

4.1.2.3. Amplifier's input current noise

e_{noi} is the output noise components produced by the amplifier's input current noise ($i_{ni} = \sqrt{2qI_{B-}\Delta f}$) which is a shot noise produced by the input bias current I_{B-} . This noise current flows directly through the feedback resistor, producing a noise voltage of

$$e_{noi} = R_f \sqrt{2qI_{B-}\Delta f}. \quad (28)$$

Choosing a FET-input operational amplifier with an I_{B-} in the picoampere range generally makes this noise component negligible for practical levels of feedback resistance. For the AD795 operational amplifier, the input current noise is $I_{B-} = 13fA$.

4.1.2.4. Amplifier's input voltage noise

e_{noe} represents output noise components produced by the amplifier's input voltage noise e_{ni} . Within the response boundary of the op amp, this noise can be calculated by

$$e_{noe} = \frac{1 + R_f C_f s}{1 + R_f C_f s} e_{ni} \quad (29)$$

This will be a high frequency noise when the capacitors dominate the noise gain. For the AD795 amplifier, $e_{ni} = 3\mu V$ below 10Hz.

4.1.2.5. Total voltage noise

The total voltage noise (e_{no}) can be obtained by adding the contributions of all the above noises. Since these noises are independent random processes which can be approximately modeled by Gaussian statistics, the total variance of voltage fluctuation at the output of the transimpedance amplifier can be obtained by adding individual variances. Therefore, the combined output voltage noise of all components is given by

$$e_{no} = \sqrt{e_{nos}^2 + e_{noR}^2 + e_{noi}^2 + e_{noe}^2} \quad (30)$$

4.1.3 Power budget of the developed SCIIB system

Assume that the maximum output power from the SLED source is 1.6 mW. The coupler introduces a loss of 6dB (75%) because of the double passes. The Fresnel reflection of the fiber endface is 4%. If counting for the two reflections at the sensor head, the total average reflected power will be 8% of the incident power. There are other losses associated with the SCIIB system. For example, the coupling loss of the fiber to the GRIN lens is about 0.2dB (4.5%). The beamsplitter splits the light into the two channels with a ratio of 50:50, which introduces another 50% power loss to each channel. The power seen by the narrow band channel will only be 25% of the original power of the full spectrum because the bandpass filter only slices a portion (10nm spectral width) of the original source bandwidth (40nm). The bandpass filter used in the system also introduces an optical loss of 60%. The maximum operating distance for the single mode fiber sensor is 10km, which will introduce a fiber loss of $2 \times 0.3\text{dB/km} \times 10\text{km} = 6\text{dB}$ (74.88%) because of the double pass of the light, where 0.3dB/km is the assumed loss at $\lambda = 1310\text{nm}$ of the single-mode fiber used in connecting the sensor to the signal processing unit. Finally, it is wise to allow a loss margin of 10dB (90%) power loss for the fiber deployment. The loss items with their estimated values are listed in Table 4-1.

Table 4-1. Optical loss mechanisms in single-mode SCIIB system

Optical loss mechanisms	Value
Coupler loss (L_c)	75%
Average Fresnel reflection of the fiber ends (r_f)	8%
GRIN lens pigtail loss (L_{GRIN})	0.2dB (or 4.5%)
Beamsplitter loss (L_{BS})	50%
Filtering loss (L_f)	75%
Bandpass filter loss (η_{BP})	60%
Fiber attenuation loss (L_f)	$10\text{km} \times 0.3\text{dB/km} \times 2 = 6\text{dB}$ (or 74.88%)
Loss margin for fiber deployment (L_{Mrg})	10dB (90%)

Therefore the optical power seen by the photodetector at the signal channel can be estimated to be

$$\begin{aligned}
 P_{in} &= P_s \times (1 - L_c) \times r_f \times (1 - L_{GRIN}) \times (1 - L_{BS}) \times (1 - L_f) \times \eta_{BP} \times (1 - L_f) \times (1 - L_{Mrg}) \\
 &= 57.6\text{nW}
 \end{aligned} \tag{31}$$

4.1.4 Signal-to-noise ratio estimation of SCIIB electronics

Based on the above analysis and the estimated optical power seen by the photodetectors of the SCIIB signal channel, we can calculate the estimated signal-to-noise ratio (SNR) of the developed SCIIB system, where SNR is defined as

$$\begin{aligned}
 SNR &= 10 \log\left(\frac{\text{average signal power}}{\text{noise power}}\right) = 20 \log\left(\frac{\text{average signal voltage}}{\text{noise voltage}}\right) \\
 &= 20 \log\left(\frac{e_s}{e_{no}}\right) = 20 \log\left(\frac{I_p R_f}{\sqrt{e_{nos}^2 + e_{noR}^2 + e_{noi}^2 + e_{noe}^2}}\right)
 \end{aligned} \tag{32}$$

where we used the fact that electrical power varies as square of the voltage.

Therefore, the signal-to-noise ratio (SNR) of the electronics of the single-mode fiber SCIIB sensor system can be calculated as shown in Table 4-2, where the noise terms are listed separately. From the table, we can see that the theoretical signal-to-noise ratio of the receiving electronics of the single-mode fiber SCIIB system is about 98.8dB (equivalent to a normalized noise level of 1.148×10^{-5}). This is, however, by no means the actual SNR of the entire system. As we will see in the analyses of next section, the optical noise will dominate the performance characteristics of the system.

Table 4-2. SNR calculation of the single-mode fiber SCIIB electronics

Items	Value
Shot noise generated voltage noise (e_{nos})	5.28 (μV)
Thermal noise of the feedback resistor (e_{noR})	1.62 (μV)
Amplifier's input current noise (e_{noi})	2.57 (nV)
Amplifier's input voltage noise (e_{noe})	3 (μV)
Total noise voltage (e_{no})	6.28 (μV)
Average signal current (I_p)	$57.6\text{nW} \times 0.95\text{A/W} = 54.7$ (nA)
Dark current of the photodetector (I_D)	15 (pA)
Average signal voltage (e_s)	$547\text{ nA} \times 10^7\Omega = 0.547$ (V)
Signal-to-noise ratio (SNR)	98.8 (dB)
Equivalent normalized noise level	1.148×10^{-5}

4.2 Optical Noise Performance of SMF SCIIB System

As discussed in previously, the basic optical components in the SMF SCIIB sensor system include the optical source (SLED), fiber coupler, optical fibers, GRIN lens, beamsplitter, and optical bandpass filter. In order to achieve the desirable performance of the sensor system, it is necessary for those optical components to perform their functions accurately. Unfortunately, environmental perturbations, such as temperature changes and mechanical vibrations, can easily introduce noises to the system through the interaction between the optical components and the outside medium. These noises may deviate the optical components from their desired functions and result in measurement errors. Therefore, it is the purpose of this section to examine the noise performance of the optical system to ensure a reliable optical design.

The interaction between the optical components and the environment disturbance could affect the optical performance of the component in four different aspects: intensity, phase, wavelength, and state of polarization (SOP). The resultant noise from these four aspects is system and component dependent. The SCIIB system is immune to the intensity noise since it has the full capability of self-compensation for the intensity fluctuation by taking the ratio of the two channels' outputs. The phase fluctuation of the optical components will not affect the system performance because the phase of the interference signal from the Fabry-Perot cavity purely depends on the sensor probe itself. The phase shift of the optical components only adds the same amount phase change to both of the interference components. This common phase shift will be eliminated from the final interference signal of interest. The analysis can thus be narrowed down to the effects of wavelength drifts and changes of the state of polarization.

4.2.1 Wavelength Drift Induced Noise

The SCIIB system measures the pressure signal by monitoring the sensor cavity length change resultant from the applied pressure. Although the sensor cavity length change is read directly from the intensity change, the generation of the signal is based on the basic principle of optical interference. The interference of two optical waves is a sinusoidal function of the phase difference between these two waves, which is inversely proportional to the optical wavelength of the source. It can be imagined that wavelength drifts will introduce a change to the interference signal and result in measurement errors. Usually, the wavelength drift induced error can be analyzed directly from the interference equation. However, the case for the SCIIB system is somewhat different because it is the spectral characteristic of the optical filter that determines the interference signal. Therefore, a detailed investigation of the wavelength drift induced error needs more careful considerations.

4.2.1.1. Spectrum characteristic change of the optical bandpass filter

Without any doubt, the change of the spectrum after the optical bandpass filter will directly shift the interference signal. A careful examination of the system reveals that the wavelength drift before the optical bandpass filter can also cause an error through the non-centered filtering and the residual interference fringe in the reference channels.

The optical bandpass filter used in the SCIIB signal channel is a Fabry-Perot type multilayer thin film filter. The spectrum characteristics of the filter are dependent on the thickness and the refractive index of the multilayer thin film, which will change with the ambient temperature because of the thermal expansion effect and the temperature dependence of the refractive index. Assuming that the center wavelength of the filter has a temperature sensitivity of $0.001\text{nm}/^\circ\text{C}$, a temperature change of 70°C (from -15°C to 55°C) will cause a maximum change of 0.07nm in the center wavelength.

Taking the derivative of both sides of Equation (11) to λ , we have

$$\frac{ds}{d\lambda} = -\gamma \frac{4\pi L}{\lambda^2} \sin\left(\frac{4\pi}{\lambda} L\right). \quad (33)$$

The wavelength drift induced error can thus be calculated by

$$\delta s = abs\left\{\gamma \frac{4\pi L}{\lambda^2} \sin\left(\frac{4\pi}{\lambda} L\right) \delta\lambda\right\}, \quad (34)$$

which reaches the maximum at the quadrature points where the sinusoidal function gives its maximum values of ± 1 , whereas,

$$\delta s_{\max} = \gamma \frac{4\pi L}{\lambda^2} \delta\lambda. \quad (35)$$

We have defined the operating range of the SCIIB system given in Equation (14). Therefore, the normalized error can be calculated by

$$\frac{\delta s_{\max}}{\Delta s_{\max}} = \frac{\gamma \frac{4\pi L}{\lambda^2} \delta \lambda}{1.6\gamma} = \frac{4\pi L}{1.6\lambda^2} \delta \lambda \quad (36)$$

The normalized error resultant from the wavelength drift of the optical filter is plotted in Figure 4-2 as the function of the initial cavity length of the sensor probe, where the wavelength drift of the filter is assumed to be 0.07nm for the operating temperature range from -15°C to 55°C. As indicated in the figure, the error is proportional to the initial cavity length. For an initial cavity length of 25μm, the normalized error is about 0.8% of the full scale of measurement.

Figure 4-2. Normalized error induced by the wavelength drift of the filter

In order to reduce the error induced by the wavelength drift of the optical filter, and also to ensure a good fringe visibility of the signal channel, the initial sensor cavity length needs to be as small as possible. On the other hand, reducing the initial cavity length would generate an optical interference in the reference channel. This residual interference in the reference channel can cause an error to the measurement results as shown in the following discussion.

Assuming that the residual interference in the reference channel has a fringe visibility of γ_r , the output from the reference channel can be written as

$$I_1' = 2RI_0[1 - \gamma_r \cos(\frac{4\pi}{\lambda} L)] \quad (37)$$

The output of the SCIIB system is then becomes

$$s' = \frac{I_2}{I_1} = \alpha \cdot \frac{1 - \gamma_r \cos(\frac{4\pi}{\lambda} L)}{1 - \gamma_r \cos(\frac{4\pi}{\lambda} L)}, \quad (38)$$

$$\approx s[1 + \frac{\gamma_r}{2} \cos(\frac{4\pi}{\lambda} L)]$$

where, s is the original SCIIB output as given by Equation (11).

Both the SLED source and the optical bandpass filter used in the SCIIB system have a center wavelength of 1310nm. However, the actual center wavelength of the source is 3.1nm off from its nominal center wavelength. As schematically shown in Figure 4-3, this will have two effects on the output of the SCIIB system: 1) the center wavelength used to calculate the output of the reference channel in Equation (37) is no longer the same as the signal channel, and 2) the intensity of the signal channel will deviate from the original level of αI .

Figure 4-3. Schematic illustration of non-centered filtering

Therefore, Equation (38) can be modified to give the new output of the SCIIB system, given by

$$s' \approx s(1 - \frac{\Delta I}{I_0})[1 + \frac{\gamma_r}{2} \cos(\frac{4\pi}{\lambda - \Delta\lambda} L)], \quad (39)$$

where ΔI is the intensity change, and $\Delta\lambda$ is the center wavelength offset.

Both the residual interference in the reference channel and the non-centered filtering themselves will not cause measurement errors directly because once the system is calibrated these deviations are fixed. However, if the wavelength of the light drifts from the original spectrum, for example, because of the temperature induced drift of the source wavelength and the fiber bending induced spectral distortion, there will be errors resulted from these changes.

From Equation (39), the normalized measurement error resultant from the wavelength drift $\delta\lambda$ can thus be calculated by

$$\left. \frac{\delta S}{S} \right|_{\max} \approx \left\{ \text{abs} \left(\frac{1}{I_0} \frac{dI}{d\lambda} \right) + \frac{\gamma_r}{2} \cdot \frac{4\pi L}{\lambda^2} \right\} \bigg|_{\lambda-\Delta\lambda} \cdot \delta\lambda, \quad (40)$$

where I is the normalized spectrum of the optical source, which can be modeled by the following Gaussian function

$$I(\lambda) = \frac{2I_0}{\sqrt{\pi}\Delta\lambda_0} \exp\left(-\frac{(\lambda - \lambda_c)^2}{\Delta\lambda_0^2}\right), \quad (41)$$

where I_0 is the total optical power, $\Delta\lambda_0$ is the e^{-1} half spectral width, and λ_0 is the central wavelength. Therefore, we have

$$\frac{1}{I_0} \frac{dI(\lambda)}{d\lambda} = -\frac{2(\lambda - \lambda_c)}{\sqrt{\pi}\Delta\lambda_0^3} \exp\left(-\frac{(\lambda - \lambda_c)^2}{\Delta\lambda_0^2}\right). \quad (42)$$

Figure 4-4 shows the calculated results of the normalized measurement error as the function of the wavelength drift given by Equation (40).

The spectrum of a semiconductor optical source is temperature dependent. The change of temperature will cause changes to both the index of refraction of the active medium and the dimensions of the resonant cavity, and hence change the spectrum of the emitting light. To reduce the spectral fluctuation of the source, a thermo-resistor and a thermal electrical controller (TEC) are usually installed very close to the source chip. These two together with the external controlling circuits form a feedback loop that helps to keep the chip temperature unchanged. With the help of the automatic thermal electrical cooling mechanism, the wavelength drift of the optical source can thus be minimized to the level of about 0.2nm.

Figure 4-4. Normalized measurement error resultant from the residual interference in the reference channel and the non centered filtering, where the initial sensor cavity length is set to be $L_0=25\mu m$.

The spectrum of the light waves transmitted in a fiber will change when the fiber is bent. The fiber bending induced spectrum change (or the fiber bending loss spectrum) is a very complicated phenomenon. Although theoretical modeling of this process is possible, it will be easier and more direct to investigate this phenomenon experimentally.

The schematic configuration of the experiment set-up is shown in Figure 4-5. The source used in the experiment was an Anritsu SLED. The output light from the source was transmitted through a section of single-mode fiber under test, and the transmitted spectrum was recorded by an optical spectrum analyzer (OSA). By manually bending the fiber to certain radii, we can study the bending introduced spectrum changes.

Figure 4-5. Experimental setup for the evaluation of fiber bending introduced spectrum change

Figure 4-6. Bending induced spectrum change test results for regular telecom single-mode fiber

Figure 4-7. Bending induced spectrum change test results for bending insensitive single-mode fiber

Two types of single-mode fibers were evaluated experimentally. In the first experiment, a section of regular telecom single-mode fiber (SMF28TM fiber made by Corning Inc.) was used to run the test. The fiber was bent to a series of radii from 12mm to 3mm. The smallest bend that might be encountered when the sensor is deployed in an oil well is about 12mm. The typical spectra of

light transmitted in the original and the bent fiber are plotted in Figure 4-6. Similar tests were also conducted using a section of bending insensitive single-mode fiber at 1300nm (purchased from Spectran Communication Fiber Technologies, Inc.), with the recorded spectra shown in Figure 4-7.

The optical interference of a broadband source is the contribution of each spectral component. For the purpose of evaluating the spectral distortion induced phase shift to the interference signal, the change of the effective central wavelength can be calculated from the recorded spectrum data. The calculated typical effective center wavelength change for regular single-mode fiber is about 0.3nm, and that of the bending insensitive fiber is about 0.2nm.

From the theories of fiber optics, the mode field radius $w(\lambda)$ of a step-index single-mode fiber can be approximated by [3]

$$w(\lambda) = a \left(0.65 + \frac{1.619}{V^{3/2}} + \frac{2.879}{V^6} \right), \quad (43)$$

where the electric field of the guided mode is assumed to have a Gaussian distribution in shape, and V is the normalized frequency of the fiber, defined as

$$V = \frac{2\pi}{\lambda} a \sqrt{n_1^2 - n_2^2}. \quad (44)$$

Here, a is the core radius, n_1 and n_2 are the refractive indices of the core and cladding respectively.

Examining Equation (43) and (44) reveals that the mode field diameter of a step-index single-mode fiber is proportional to the wavelength of the light. The light of longer wavelength will have a larger mode field diameter when it is transmitted in the fiber. Intuitively, the larger the mode field diameter, the higher loss it will be when the fiber is under bending because the optical energy is less confined inside the waveguide. This explains qualitatively why the long wavelength end of the spectra suffers larger loss compared to the short wavelength end, as shown in Figures 4-6 and 4-7. Because the mode field diameter of the regular telecommunication fiber is larger than that of the bending insensitive fiber, the loss of the regular fiber is higher than that of the bending insensitive fiber.

Bending a single-mode fiber can also cause the coupling between the guided mode and the cladding modes. The coupling between modes results in the transfer of energy between these modes, which is both wavelength and bending status dependent. Within the spectral range of the source, the coupling can be in favor of certain wavelength components than others depending on the status of bending. This explains the ripples in the transmitted spectrum when fiber is under bending.

In general, comparing the experimental results shown in Figures 4-6 and 4-7, the distortions of the spectrum in the bending insensitive fiber are smaller than that of the regular telecom fiber

with the same bending radius. Even under severe bending, the transmitted spectrum of the bending insensitive fiber still does not exhibit spectral ripples. The larger distortion of the spectrum in regular telecom fibers is mainly due to the large mode field diameter of the waveguide. However, the difference between these two fibers is small for a relatively large bending radius ($>12\text{mm}$).

4.2.2 Change of SOP Induced Noise

The SLED used in the SCIIB system outputs almost linearly polarized light. As the light propagates inside the SMF, the state of polarization will be changed because of both intrinsic birefringence and extrinsic birefringence. Although the fiber Fabry-Perot sensor probe is polarization insensitive, the receiving optics of the SCIIB system is however polarization dependent. This is largely due to the residual polarization dependence of the optical beamsplitter.

4.2.2.1. Residual polarization sensitivity of the beamsplitter

The SCIIB receiving optics uses low polarizing cubic beamsplitter (made by OptoSigma Inc.) with a central operating wavelength of 1310nm to separate two channels for signal and reference. As shown in Figure 4-8, the beamsplitter has a residual polarization dependence of about 10% in the wavelength range (1250nm-1350nm). This will result in the non-constant splitting ratio that is dependent on the state of polarization of the input light.

Figure 4-8. Transmission characteristics of the beamsplitter

Assuming that the splitting ratio of the beamsplitter as a function of the input SOP given by

$$r(SOP) = \frac{I_1(SOP)}{I_2(SOP)} \neq 1:1, \quad (45)$$

the SCIIB output thus becomes

$$\begin{aligned} s' &= r(SOP)s \\ &= r(SOP)\alpha[1 - \gamma \cos(\frac{4\pi}{\lambda}L)] \end{aligned} \quad (46)$$

As indicated in Equation (46), the change of SOP will directly cause a normalized measurement error which can be calculated as

$$\frac{\Delta s}{s} = r(SOP) - 1. \quad (47)$$

From Figure 4-8, the maximum deviation of $r(SOP)$ from its desired value (1:1) can reach 10% if the SOP of the light input to the beamsplitter changes from one polarization (p) to another (s). Therefore, the change of SOP can potentially introduce a normalized measurement error as large as 10%.

4.2.2.2. Polarization of single-mode fibers

If the fiber is perfectly circular with circularly symmetric refractive index distribution, the two LP_{01} (or HE_{11}) modes will perfectly degenerate. That is both x-polarized ($E_y=0$) and y-polarized ($E_x=0$) LP_{01} modes have the same propagation constant [4,5]. However, actual fibers generally exhibit some ellipticity of the core and/or some anisotropy in the refractive index distribution due to anisotropic stresses. This results in two different propagation constants for the x-polarized (β_x) and y-polarized (β_y) LP_{01} modes, leading to perturbations of the state of polarization of the light transmitted by the fiber. The birefringence of the fiber ($\Delta\beta$) is usually defined as

$$\Delta\beta = \beta_y - \beta_x. \quad (48)$$

The single-mode fiber in the status of bending can be viewed as a wave plate with its phase delay unknown due to the random number of bends and the random value of bending radius when the fiber is deployed into an oil well. For a linearly polarized input light, the SOP of the output light can thus be arbitrary (linearly polarized in any possible direction, circularly polarized, or elliptically polarized). To be conservative, the maximum estimated error of 10% as given by Equation (47) is valid for the entire case.

5.0 System performance optimization

In the two previous sections, the electronic and the optical noises of the SCIIB sensor system were studied in detail. The typical values of these errors are summarized in Table 5-1 for comparison.

It is shown in the table that the electronic noise is very small compared to the optical noises. Therefore, the emphasis of the system optimization should be placed on the improvement of the optical system. Among the 4 items of optical noises, the change of SOP has the most significant effect on the system performance. This noise therefore must be reduced. The noises resultant from the residual interference in the reference channel and the non centered filtering can also be reduced by the proper design of the system. However, the temperature dependence of the optical bandpass filter is an almost fixed error which little can be done due to the limited commercial availability of the components.

Table 5-1. Typical electronic and optical noises for the SCIIB sensor system

Noise sources	Typical Values
Electronics noises	0.00115%
Optical noises	
1. Spectral drift of the optical bandpass filter	0.8% (from -15°C to 55°C @ $L_0 = 25\mu\text{m}$)
2. Residual interference in the reference channel	0.0458% (0.5nm wavelength drift @ $L_0 = 25\mu\text{m}$)
3. Non centered filtering	0.0213% (0.5nm wavelength drift)
4. Change of SOP	10%

5.1 Optical system optimization

5.1.1. Discussions on the residual interference in the reference channel

As indicated in Equation (38), the measurement error resultant from the residual interference in the reference channel is proportional to the fringe visibility of the residual interference (γ_r), which is inversely proportional to the initial sensor cavity length. Therefore, increasing the initial sensor cavity length will help to reduce the residual fringe visibility in the reference channel and hence reduce the corresponding measurement error.

On the other hand, Equation (38) also reveals that the measurement error is also proportional to the initial cavity length (L_0). The longer the initial sensor cavity, the larger the measurement error. Therefore, the smallest measurement error will result from the balance between these two effects. In order to find an optimal initial sensor cavity length, several sensors with different cavity lengths were made. The experimental results and the theoretical simulation as shown in Figures 2-2 through 2-5 indicate that the visibility of the residual interference in the reference channel decreases very fast as the cavity length increases before it reaches $20\mu\text{m}$. However, after $25\mu\text{m}$, the visibility decreases very slowly as the sensor cavity length increases. Therefore, the sensor cavity length is chosen to be $25\mu\text{m}$ in the final design.

5.1.2. Reduction of the non-centered filtering induced error

As shown in Figure 4-4, measurement error is proportional to the offset between the center of the optical bandpass filter and that of the source spectrum. The closer match of the two center

wavelengths will reduce the measurement error. To reduce the mismatch between these two center wavelengths, the optical bandpass filter was rotated by an angle of about 10° from the normal incidence which it was installed. By doing this, the mismatch between the two center wavelengths was reduced within 0.5nm. The corresponding measurement error was reduced from 0.0213% to 0.0035% by estimation.

5.1.3. Reduction of the change of SOP induced error

The change of SOP can cause a large measurement error mainly through the residual polarization sensitivity of the beamsplitter used in the SCIIB system. Due to the limitation of the technology in making the beamsplitter, it is difficult to find a beamsplitter with a splitting ratio purely independent to the state of polarization of the input light. However, if the input light is totally unpolarized natural light, even using a polarization-sensitive beamsplitter, the splitting ratio can be maintained constant and the polarization issue will not be a concern at all. This naturally leads us to use a depolarizer to minimize the change of SOP induced error.

By definition, a depolarizer is an optical device transforming polarized (or partially polarized) light into naturally unpolarized or depolarized light. The Loyt depolarizer is made of two optical crystals (L_1 and L_2) cut from the same material. The neutral lines of crystal L_2 are aligned perfectly with the bisectors of the neutral lines of L_1 . These two optical crystals can be characterized by the optical phase delays δ_1 and δ_2 . If the optical conditions of the two crystals satisfy 1) the phase lag of the first crystal is larger than the coherence length L_c of the light, and 2) the second crystal (L_2) is more than twice as thick as the first one (L_1). If these two conditions are satisfied, the light emerging from the Loyt depolarizer will be effectively unpolarized when it is seen by a wide-spectrum detector.

All the above discussions suggest that if a Loyt depolarizer can be installed right before the light propagating into the beamsplitter so that the beamsplitter and the photodetectors behind effectively see unpolarized light emerging from the depolarizer no matter how the state of polarization changes in front of the depolarizer. Thereafter the splitt

5.2.1 Correction for the dark current induced bias

The dark current of the photodetector will add a constant bias to photocurrent of interest. Although the dark current of the InGaAs detector used in the SCIIB system is very small (in the order of 15 pA), the resultant bias can affect the measurement result to some extends due to the relatively low optical power reflected from the sensor probe. To investigate the dark current induced error, let's assume that the signal currents of the two channels are I_{p1} and I_{p2} with the corresponding the dark currents of I_{d1} and I_{d2} respectively. The SCIIB ratio can thus be written as

$$s' = \frac{I_{p1} + I_{d1}}{I_{p2} + I_{d1}} = \frac{I_{p1}}{I_{p2}} + \frac{I_{d1}}{I_{p2}} + O^2, \quad (49)$$

where O^2 is the second or higher order terms of I_{d1} and I_{d2} , which will be neglected from the analysis. The corresponding deviation from the ideal output ratio is

$$\Delta s = s' - s \approx \frac{I_{d1}}{I_{p2}}. \quad (50)$$

Therefore, the normalized error resultant from the dark current bias within the linear range of operation becomes

$$\frac{\Delta s}{s} = \frac{I_{d1}/I_{p2}}{I_{p1}/I_{p2}} = \frac{I_{d1}}{I_{p1}}, \quad (51)$$

where, I_{p1} should be confined in the linear operating range of the system.

Figure 5-1. Normalized measurement error resultant from the dark current bias

The normalized error is plotted as a function of the normalized signal level in Figure 5-1, where the average signal current is assumed to be 54.7nA and the dark current is 15pA adopted from Table 3. As shown in the figure, the measurement error resultant from the dark current bias can reach 0.07% when the signal level is low (close to the valley of the interference fringe).

Because the final ratio function is performed digitally by the host computer, the correction of the dark current bias becomes relatively easy. We can record in advance the output voltage of the two SCIIB channels when the optical source is turned off. The dark current is almost a constant when the photodetector is chosen. Therefore, the dark current bias can be eliminated from the final ratio using

$$s = \frac{V_1 - V_{d1}}{V_2 - V_{d2}}, \quad (52)$$

where V_1 and V_2 are the output signal voltages, and V_{d1} and V_{d2} are the recorded dark-current voltages of the two channels respectively.

5.2.2 Balance the optical power of the two channels

Because of the very large amplification factors of the transimpedance amplifiers used in the SCIIB system, the nonlinearity of the amplifiers could be a concern. However, the nonlinearity of the amplifiers can be compensated if the two amplifiers are exactly the same. Another reason to match these two amplifiers is the consideration of the temperature dependence. The resistances of the feedback resistors used in the transimpedance amplifiers will change as the environmental temperature fluctuates. If they changes in the same direction and in the same amount, by taking the ratio of the two outputs, the temperature fluctuation will have very little effects on the system output.

To be able to match the two transimpedance amplifiers, we need to balance the optical power input to the two photodetectors. Because an optical bandpass filter is used in the signal channel to increase the coherence length, the signal channel will see less optical power than the reference channel. In order to balance the two channels in terms of the optical power, an optical neutral density filter can be inserted into the reference channel with a flat spectral response within the spectral range of interest, which introduces additional attenuation to the optical intensity of the reference channel.

6.0 Evaluation of the SCIIB Signal Processing Unit

In this section, we will concentrate on the evaluation of the SMF SCIIB instrumentation system (without the sensor probe). By separating the sensor probe from the SCIIB instrumentation, we will be able to isolate problems for future development work.

6.1 Evaluation of the self-calibration capability

The SCIIB technology can self-compensate for source power fluctuations and fiber loss variations by self-referencing the two channels output. To evaluate the self-calibration capability of the SCIIB signal processing method, we conducted an experiment using the developed SCIIB instrumentation system.

Figure 6-1. SCIIB outputs versus driving current of the optical source

Without connecting to the sensor probe connected to the system, the output power of the source (SLED) was changed by changing the driving current of the source chip. With the endface of the lead-out fiber well cleaved, the SCIIB instrumentation system should output a constant ratio though each channel's output could change when the total optical power was changed. In the experiment, two multimeters were used to record the two channels' output voltages. Then the ratio of them was calculated manually. Figure 6-1 plots the recorded two channels' outputs as well as their ratio with respect to the driving current of the light source.

Figure 6-2 shows the magnified change of the SCIIB ratio as a function of the normalized optical power of the source. As shown in the two figures, the ratio of the two channels only changes about 0.3% as the total optical power changes up to 50%.

Theoretically, changing the driving current of a semiconductor optical source would also change the spectrum in addition to the optical power change. As discussed previously, the distortion of the source spectrum would also introduce error to the measurement result through the non-centered filtering effect. Therefore, the error shown in Figure 6-2 has also indicated the contribution from the source spectrum distortion. Nevertheless, the experimental results reveal that the SCIIB signal processing has a good self-compensation capability as expected.

Figure 6-2. Change of SCIIB output ratio versus the normalized source power change

6.2 Evaluation of the polarization sensitivity

As proposed in Section 5.3, we used a fiber optic depolarizer to reduce the system sensitivity to the change of state of polarization due to fiber bending, which is unavoidable in actual fiber deployment.

To get an idea of how severe the polarization state would affect the system performance, we first test the SCIIB instrumentation without the depolarizer. Again, the system was tested without the sensor probe and the signal was directly from the reflection of the fiber endface. To change the SOP, we bent the fiber into a circle of different radii and flipped the fiber circle to different orientations. The SCIIB two channels' outputs were then recorded using an oscilloscope as shown in Figure 6-3. The ratio of these two outputs are plotted in Figure 6-4. As we see, the two channels' outputs were sensitive to the change of SOP, and moreover, they did not follow each other due to the polarization effect. The peak-to-peak variation in this case was about 5% of the average ratio.

The experiment was conducted again with the depolarizer connected to the system. The two channels' outputs are shown in Figure 6-5, and the ratio of them is shown in Figure 6-6. With the fiber optic depolarizer, the two outputs followed each other very closely. The maximum variation of the ratio was reduced to about 0.5%, showing an improvement of one order of magnitude.

Figure 6-3. SCIIB two channels' outputs as SOP of the fiber changes
(without the depolarizer)

However, the experiment also indicated that the dependence of the SCIIB ratio was still large compared to the analytical prediction given in Section 6.2. The fiber optic Lyot depolarizer purchased from Noah Industries, Inc. was tested using a wide-spectrum light source. The optical

Figure 6-4. Ratio of the SCIIB two channels' outputs as SOP of the fiber changes
(without the depolarizer)

bandpass filter used in the system had a spectral width of 10nm, which was narrower than the spectral width of the light source that had been used to test the depolarizer. The specified 20dB extinction ratio of polarization suppression might not be true for the signal channel. Therefore, we would expect to have larger polarization dependence of the SCIIB output ratio than the analytical prediction.

Figure 6-5. SCIIB two channels' outputs as SOP of the fiber changes (with the depolarizer)

Figure 6-6. Ratio of the SCIIB two channels' outputs as SOP of the fiber changes (with the depolarizer)

6.3 Dynamic error of the SCIIB instrumentation

The change of the environmental temperature could have multiple effects on the SCIIB instrumentation system. As discussed in the last chapter, the spectrum of the light source, the spectral characteristics of the optical bandpass filter, the beamsplitter, the amplifiers and the photodetectors are all temperature dependent. The change of the environmental temperature will eventually cause measurement errors.

Experiments were also conducted to evaluate the dynamic error of the developed SCIIB instrumentation system. Again, the system was not connected to the sensor probe and just took the reflection from the fiber endface as the signal. In the experiment, the SCIIB system was put in an electronic oven. A thermal couple was placed inside the oven to record the actual temperature inside the oven. The oven was then heated up to 57°C stabilized for about half an hour. Then the oven was shut down. During the period that the temperature inside decreased slowly, the SCIIB two channels' outputs were recorded using two multimeters every degree Celsius from 57°C to 20°C. The recorded outputs are plotted as shown in Figure 6-7, with their ratio shown in Figure 6-8. As shown in Figure 6-8, the outputs of the two channels changed as the environmental temperature changed. However, the two channels followed each other in the same direction. The change of their ratio was within 1% within the testing temperature range of 37°C. The dynamic error of the SCIIB instrumentation system is about 0.027%/°C.

Due to the limitation of the experimental equipment, we could not create environmental temperature changes lower than the room temperature. However, the above-mentioned experimental results mentioned above made us believe that the SCIIB instrumentation system could maintain its accuracy of a few percent of the full scale within the specified temperature range of operation. Moreover, the instrumentation is usually placed in a control room with a relatively small fluctuation of the environmental parameters. The actual dynamic error will be far small.

Figure 6-7. SCIIB instrumentation dynamic error test
(two channels' outputs)

Figure 6-8. SCIIB instrumentation dynamic error test (SCIIB ratio)

7.0 SCIIB Sensor Probe Fabrication and Evaluation

Up to now, the method used in fabricating extrinsic Fabry-Perot interferometer (EFPI) sensors has been limited to using epoxy to bond two fibers with their endfaces cleaved inserted into a capillary tube with a proper inner diameter. Although extensive research has been conducted to find high performance epoxies to fabricate EFPI sensor probes, the fabricated sensors generally failed to provide satisfactory performance in terms of mechanical strength and thermal stability. Another constraint of the epoxy-based sensors is that the maximum operating temperature is limited by the epoxy which is relatively low. Because epoxies have a coefficient of thermal expansion (CTE) different from that of the fibers and the tube, epoxy bonded sensors are usually very sensitive to temperature changes, which makes it difficult to use those sensors to measure parameters other than temperature. It is also found difficult to control the sensor initial cavity length and the bonding size because the relatively long curing time of the epoxy. Furthermore, the viscosity of the epoxy bonding will also degrade the frequency response of the EFPI sensor in case of high frequency signals need to be measured.

Telecommunication optical fibers are usually made by doping very small amount of germania into pure silica glass. Fused silica capillary tubes of various sizes are also commercially available. Silica glass is an amorphous material. When heated to a certain temperature (about 1500°C), it becomes soft [88]. This indicates that we can use thermal fusion techniques to bond the fiber and the capillary tube together. By locally heating the fiber and tube assembly to a temperature above which the glass is softened, the tube and the fiber can flow into each other and locally join to form a solid bond.

A major research task of the proposed research is to develop an automated SCIIB sensor fabrication system. The sensor fabrication system uses a high-energy carbon dioxide (CO_2) laser to provide the heating power and a whitelight spectrum interferometry mechanism to monitor the cavity length of the sensor in real-time during fabrication. This system, as its detailed design reported in last year's annual report, allows the automatic fabrication of a large quantity of high performance SCIIB sensors at a low cost.

7.1 Improvement of the Sensor Fabrication System

Since last annual report, the research work on the sensor fabrication system has been concentrated on the improvement of the system performance. Solid progresses have been made to improve both the mechanical strength of the sensor probe and the repeatability of sensor fabrications.

7.1.1 Improvement of the mechanical strength of the sensor probe

To improve the mechanical strength of the sensor probe, a mirror system has been designed and incorporated to the system. In the previous design of the sensor fabrication system, the output beam from the CO_2 laser heated the capillary tube and fiber assembly from one direction, which resulted in the non-uniform temperature increases of the assembly. Many sensors fabricated were found either not completely sealed or too many built-in residual stresses after fabrication.

The improvement of the mechanical strength of the sensor probe was achieved by adding a set of copper mirrors to the fabrication stage, as schematically shown in Figure 7-1. Two mirrors made by polishing the copper plates were placed underneath the sensor assembly. The angle of the two copper mirrors were set to be 120° . The CO_2 laser beam was also aligned to input to the assembly at an angle of 60° . Therefore, the input beam and the two reflected beams from the mirrors heat the sensor assembly at the three directions evenly distributed. Experiments were also conducted to find the optimal CO_2 laser power and the duration. With the mirror set described above, the sensor assembly can be bonded uniformly to minimize the residual stresses.

7.1.2 Improvement of the repeatability of sensor fabrication

To improve the repeatability of sensor fabrication, several measures have been taken. These include the improvement of the measurement accuracy of the whitelight interferometric cavity length monitoring system, addition of a PZT stage system to tune the initial cavity length precisely, and a computer program to control the adjustment of the initial cavity length after sensor is bonded.

As reported in last annual report, the whitelight interferometric cavity length monitoring system was tested to have the accuracy of $0.02\mu\text{m}$ for single-mode system and $0.002\mu\text{m}$ for multimode system. This is however not high enough to meet the sensor fabrication requirements. Research efforts have been focused on the new algorithms to improve the accuracy of the whitelight system. The mass centroid algorithm was implemented to show a big improvement of locating the peak or valley positions. Also, the peak or valley tracking algorithms were added to the system

Figure 7-1. Schematic illustration of the copper mirror set in sensor fabrication system

which dramatically improved the wavelength resolution of the system. The current accuracy of the whitelight system has been tested to be $0.001\mu\text{m}$ for single-mode fiber sensors and $0.0005\mu\text{m}$ for multimode fiber sensors. This is more than one order of magnitude improvement.

In addition to the improvement of the accuracy of the whitelight system, a high resolution PZT stage was also incorporated to the sensor fabrication system. With the completion of the driving circuits, and the computer control algorithms, the PZT stage allowed us to tune the sensor cavity length after the capillary tube and fiber was bonded together. By reheating the assembly with 80% of the CO_2 laser power required for bonding, and by controlling the PZT stage to pull the fiber with a resolution of 2nm, SCIIB sensors can now be fabricated repeatedly with the initial cavity lengths adjusted exactly to the starting point of the linear region.

7.2 SCIIB Sensor Fabrication

With the completion of the sensor fabrication system, we are now ready to fabricate SCIIB sensor probes. Fibers used to fabricate the sensor probe are carefully cleaned and cleaved using a York fiber cleaver. The capillary tube is also cleaned and cleaved to the desired length. With the help of the microscope, two fiber ends prepared by the cleaver are then inserted into the capillary tube and held on the positioning stages. By adjusting the micromotion stage system, the two fibers are moved to the preset positions where the desired initial sensor cavity length is obtained. By moving the 2-dimensional translation stage underneath the micromotion stage system, the fiber and capillary tube assembly is brought to the center of the laser spot. The CO_2 laser emits light to heat the assembly with its power level and duration controlled by the computer program. After one side of the sensor is fused, the fiber and capillary assembly is then move to the other side to perform the same fusion process.

Figure 7-2. Microscopic photograph of the SCIIB sensor probe
(Gauge length: 1.5mm, initial cavity length: 25.74 μ m)

Figure 7-2 shows the photograph of a typical sensor probe imaged by the microscope. In the picture, we can clearly see the sensor cavity formed by the fiber endfaces and the two fusion points. So far, the shortest sensor gauge length that can be fabricated with the system is 0.5mm for the single-mode fiber-based sensor and 0.7mm for the multimode fiber-based sensor, respectively. It is very difficult to further reduce the sensor gauge length because the fiber endfaces can be damaged resulting from the too close fusion point.

7.3 Evaluation of the SCIIB sensor probe

As discussed in Chapter 6, the SCIIB sensor probe is fabricated using the controlled thermal bonding method, by which the silica glass fibers are fused with the fused silica glass capillary tube. Therefore, the sensor probe is expected to have a strong mechanical strength and can sustain high pressures. The sensor temperature model given in Chapter 6 also reveals that the SCIIB pressure sensor has very small temperature dependence. Experiments were conducted to evaluate the sensor's survivability and temperature dependence.

7.3.1 Survivability of the sensor probe

Up to the current date (15 August 2000), hundreds of SCIIB sensor probes have been made using the developed fabrication system. Before the sensors can be used in harsh environments, they must be tested to ensure a complete sealing at the two fusion points because an imperfect sealing would result in the intrusion of the outside medium and degradation of the sensor performance. More than one hundred sensors were first tested in the water environment of high pressure (>3000 psi) and high temperature (>200°C). So far, only two sensors were found to leak water into the cavities during the test. The majority of the sensors successfully survived the test. This made us believe that the controlled thermal bonding method could provide sensor probes strong enough to survive in harsh environments.

7.3.2 SCIIB sensor annealing

The capillary tube and glass fibers are fused together in a very short time period during the sensor fabrication process. It will be a reasonable concern about the residual stresses left built in the bonding regions due to the very large temperature difference. These residual stresses, when they release slowly, will cause sensor to drift from its original calibrated operating point. Therefore, the sensor must be properly annealed to release the built-in stresses prior to sensor calibration.

The sensor annealing was done using an electrical furnace at a temperature of 600°C for 24 hours. During the annealing process, the temperature was increased and decreased slowly to avoid further stress built in. In order to see how the annealing affects on the sensor, five sensors were annealed twice under the same experimental condition, and the cavity lengths of the five sensors were monitored using the whitelight interferometer during the entire annealing process. The recorded changes of the cavity lengths are listed in Table 7-1.

Table 7-1. Sensor cavity length change before and after annealing

Sensor index	Gauge Length (mm)	Cavity length before annealing (μm)	Cavity change first annealing (nm)	Cavity change second annealing (nm)
1	0.7	20.0872	-37.2	2.7
2	1.0	39.6614	-15.8	3.3
3	1.0	29.1794	-68.4	*
4	1.0	20.4749	-32.2	1.9
5	0.7	21.3901	-13.1	3.4

*The sensor was broken after the first annealing because of mishandling.

As shown in the table, the changes of the sensor cavity lengths after the second annealing became very small compared to the first one, which indicate that the annealing process did improve the stability of the sensor. Although the sensors used in the experiment were chosen with different parameters (gauge lengths and initial cavity lengths) in hope to find the regularity of the annealing effect on the sensors, the results shown in Table 7-1 did not indicate an obvious relationship between the sensor parameters and the changes of cavity lengths except that all the sensors showed a decrease in their cavity lengths after the annealing process. Nevertheless, the experiment indicated that the annealing process did cause a large change of the sensor cavity length with respect to the linear range of operation (about 200nm). Therefore, the sensor annealing is proved to be necessary to assure the performance of the sensor.

7.3.3 Temperature dependence of the SCIIB sensor probe

The temperature model of the SCIIB sensor probe has been given in Chapter 6, where the analysis showed that the temperature sensitivity depends on the sensor gauge length, the initial cavity length, and the CTEs of the fiber and the capillary tube. It is possible to design the sensor according to the temperature model to have very small or even zero temperature sensitivity.

The actual CTEs of the fiber and the tube can deviate from the nominal values due to the small difference in the chemical composition among the materials used by different manufacturers. It is very difficult to determine the actual temperature dependence of the sensor probe by just referencing the nominal CTEs due to the extremely high accuracy required. The actual temperature dependence of the sensor probe therefore has to be measured experimentally.

7.3.3.1. Multimode SCIIB sensor probe

The experimental set-up included an electric furnace with its maximum temperature up to 1100°C and an Omega CN76000 thermometer to read the temperature with an accuracy of 0.1°C. The multimode sensor probe and the thermocouple were put side by side in the furnace, and the temperature was increased from room temperature (30°C) to 810°C in steps of 10°C. Both the SCIIB sensor output and the thermometer output were recorded for comparison.

Figure 7-3. Multimode SCIIB sensor temperature sensitivity test result

The capillary tube used to fabricate the multimode sensor was made of fused silica purchased from Polymicro Technologies, Inc. The inner diameter of the tube is 130 μm , and the outer diameter is 365 μm . The sensor had an effective gauge length of 0.7 mm, and the initial cavity length of 5.160 μm . The sensor output versus the increase of the temperature is plotted in Figure 7-3.

As shown in Figure 7-3, the SCIIB system output was estimated to cover about 70% of the change from the peak to the valley of an interference fringe when the temperature changed from 30°C to 810°C. It was known that half of the interference fringe corresponded to a sensor cavity length change of a quarter of the central wavelength. Therefore, with the source central

wavelength of 850 nm, the temperature sensitivity of the multimode sensor could be estimated by the following equation

$$s_{t,m} = \frac{70\% \times \frac{1}{4} \times 850[\text{nm}]}{(810 - 30)[^{\circ}\text{C}] \times 0.7[\text{mm}]} = 2.7 \times 10^{-7} [\frac{1}{^{\circ}\text{C}}]. \quad (53)$$

Although the temperature sensitivity given in Equation (53) is only estimation, the result agrees with what the temperature model predicts. The experimental results indicate that the multimode fiber-based sensor probe has a large temperature dependence compared to its linear operating range. This is mainly due to the large CTE of the fiber which results from the large quantity of dopants used to increase the core refractive index and fill the relatively large core. The large difference between the CTE of the fiber and that of the fused silica tube makes the multimode fiber-based sensor probe have a large temperature dependence. When the multimode fiber-based sensor is used for pressure measurement in harsh environments where the temperature variation could be large, the large temperature dependence can introduce an unacceptable error to the final result.

7.3.3.2. Single-mode fiber SCIIB sensor probe

Single-mode fibers have a smaller core diameter and refractive index difference compared to multimode fibers. The smaller amount of dopants in single-mode fibers makes the single-mode fiber have a CTE very close to that of fused silica, and hence less temperature dependent compared to the multimode fiber sensor.

To determine the actual temperature sensitivity of the single-mode fiber-based sensor probe and also in hope to find an optimal design of the sensor probe to achieve zero temperature dependence, we fabricated five single-mode fiber sensors and measured their temperature sensitivity experimentally. The parameters of these five sensors are listed in Table 7-1. The experiments were conducted using the same electrical furnace for the sensor annealing. Because the temperature sensitivity of the single-mode sensor is very low, it is almost impossible to increase the temperature high enough to cover one-half interference fringe as we did for the multimode fiber sensor. The whitelight interferometry was thus used to measure the sensor cavity length. Figure 7-10 shows the recorded sensor cavity lengths measured as the temperature inside the furnace increased from room temperature up to 650°C at the step of 50°C.

As shown in Figure 7-4, all the sensors showed a decrease in the cavity length as the temperature increased. Also, it was found that a shorter gauge length resulted in smaller temperature sensitivity.

Figure 35. Temperature sensitivity test results of single-mode sensor probes

Although efforts were attempted to find the exact CTEs of the fiber and the capillary tube by solving the linear equations formed by the experimental data, the results conflicted with each other. The reason was believed the accuracy of the whitelight interferometry was not high enough compared to the required resolution. In order to provide meaningful data for the equation solving to find the actual CTEs, a more accurate method for displacement measurement must be used. Nevertheless, the experimental data did provide some information of the temperature dependence of the sensor. For example, a sensor with a gauge length of 0.7mm (corresponding to 4000psi pressure measurement range), and an initial cavity length from 20 μ m to 30 μ m will have a temperature sensitivity of 0.02nm/°C (or $2.86 \times 10^{-8}/^{\circ}\text{C}$), which is an order of magnitude lower compared to that of the multimode fiber sensors.

8.0 SCIIB Pressure Sensor System Performance Evaluation

With a calibrated sensor, we are ready to evaluate the performance of the developed SCIIB pressure sensor system. The performance characteristics that have been evaluated so far include the linearity, hysteresis, resolution, repeatability, system stability, temperature cross sensitivity, and over pressure capability.

8.1 Linearity of the Sensor System

Due to the sinusoidal nature of the interference signal, the direct output from the SCIIB pressure sensor is a nonlinear function of the applied pressure. However, the calibration process can linearize the SCIIB output data by polynomial curve fitting. To assess the residual nonlinearity of

the sensor system, we examined the measurement result after calibration, as shown in Figure 8-1, with respect to the applied pressure given by the APP system. The sensor used in the test was a single-mode fiber sensor with the gauge length of 0.5mm, the initial cavity length of 25.46 μ m, and the interference fringe visibility of 70%. The magnified deviation between the calibration line and the straight line is plotted in Figure 8-2. As we see, the maximum deviation is about 9psi. If we normalized the nonlinearity with respect to its full dynamic range of 8500psi, the normalized nonlinearity error is less than 0.1% of the full scale of pressure measurements, which is the best accuracy offered by the pressure calibration system.

Figure 8-1. SCIIB pressure sensor system calibration lines

Figure 8-2. Nonlinearity of the SCIIB pressure sensor system

8.2 Hysteresis of pressure measurement

Hysteresis of the pressure sensor can be measured by cycling the applied pressure between the minimum and the maximum of the operating range in both increasing and decreasing directions. The hysteresis can be calculated as the largest difference among the output readings of the pressure cycles. The SCIIB pressure sensor probe is made of silica glass material and the operating range of the sensor in terms of pressure induced strain is very small. Therefore, the hysteresis of the sensor probe is expected to be very small. Nevertheless, experiments were conducted to evaluate the actual hysteresis of the SCIIB sensor probe. The evaluation was conducted using the APP pressure system after the sensor system was calibrated. The applied pressure was first increased to the maximum operating range of 8500psi at the step of 400psi. The pressure was then decreased to the atmosphere pressure after it was maintained at 8500psi for several minutes. The measurement results are shown in Figure 8-3. The experimental results confirm our expectation. There was no noticeable hysteresis found within the entire operating range.

Figure 8-3. Hysteresis of the SCIIB pressure sensor

8.3 Resolution of pressure measurement

The resolution of the sensor system is usually interpreted by its standard deviation of a series of pressure measurements. It is common to use twice the standard deviation as the direct measure of resolution. The evaluation of the sensor resolution was performed using a calibrated sensor with the linear range of 8500psi. The sensor was exposed to the atmosphere where the pressure reading from the sensor should be zero. The data from the SCIIB system was sampled at a rate of 50 samples per second for one minute, which should be high enough compared to the system's frequency response of 15Hz. The pressure measurement outputs within the one-minute sampling period are plotted in Figure 8-4. The standard deviation of the pressure data within this time

period was calculated to be $\sigma=0.121\text{psi}$. Therefore the resolution of the sensor system was estimated to be $2\sigma=0.242\text{psi}$. The normalized resolution with respect to the dynamic range of the system was 0.003% of the full scale.

Figure 8-4. Standard deviation measurement of the SCIIB pressure sensor

It must be pointed out that the resolution of the sensor is not constant within the entire operating range due to the non-linear nature of the interference signal. However, by confining the operating range of the SCIIB sensor within its semi-linear range of an interference fringe, the resolution of the system should be retained within 60% of the maximum resolution as defined by Equation (14).

8.4 Repeatability of pressure measurement

Repeatability of the sensor can be measured by applying pressure to a certain preset point repeatedly only from one direction (increasing or decreasing). The largest difference of the sensor output readings can be used to specify the repeatability of the sensor. The same calibrated single-mode sensor was used to evaluate the repeatability of the system. Using the APP system, two consecutive measurements up to the full operating range of the sensor were performed with the results shown in Figure 8-5. For comparison purposes, the original calibration data is also shown. The deviation of the two measurement results with respect to the calibration data are plotted in Figure 8-6.

As shown in Figure 8-6, the maximum deviation between the measured pressure and the calibrated pressure was within $\pm 13\text{psi}$. The normalized repeatability of the sensor system with respect to its dynamic range was therefore $\pm 0.15\%$ of the full scale.

Figure 8-5. Repeatability test result of the pressure measurement

Figure 8-6. Deviation of the measured pressure with respect to the calibration data

8.5 System stability test

The same single-mode sensor with the operating range of 8500psi was also used to test the system stability. The sensor was kept in the pressure test chamber of the APP system for 24 hours starting from 4:00pm in the afternoon. The pressure of the chamber was maintained to the atmosphere pressure. The data acquisition system was programmed to sample the sensor's output every 20 seconds. The test result is shown in Figure 8-7. By processing the data, the maximum peak-to-peak pressure variation within the 24-hour time period was 3.3 psi. The normalized

maximum variation was thus 0.04% of the full dynamic range. The test results also showed that the variation of the data was not one-directional.

Figure 8-7. System stability test over 24 hours

It must be said that the complete evaluation of the system stability needs much longer test period (for example, one year). Therefore, the stability test result of 24-hour period was hence not quite conclusive.

8.6 Temperature cross-sensitivity of pressure measurement

The cross sensitivity to temperature could result in errors of the pressure measurement when the environmental temperature changes. The construction of the APP pressure calibration system allowed us to characterize the temperature cross sensitivity of the SCIIB pressure sensor by measuring pressures at different elevated temperatures. As shown in Figure 8-8, the same single-mode fiber sensor with the dynamic range of 8500psi was tested at temperatures of 24°C, 88°C, and 206°C respectively. Figure 8-9 shows clearly the measurement errors at the two elevated temperatures. The maximum deviation was 215psi at 88°C and 307psi at 206°C respectively. The maximum temperature cross sensitivity was thus calculated to be 0.04% per degree Celsius.

It was also noticed that the large errors were found at the low and high pressure range where the nonlinear effects became the largest. The temperature cross sensitivity could thus be reduced by sacrificing the dynamic range of the sensor.

Figure 8-8. Temperature cross sensitivity test of the SCIIB pressure sensor

Figure 8-9. Pressure measurement errors resultant from the temperature dependence

8.7 Overpressure capability test

In real downhole applications, pressures higher than the nominal values might be encountered due to the use of steam flood to pump the oil to the surface. It is therefore very important for the sensor to be able to sustain burst pressures higher than its dynamic range. The overpressure capability of the SCIIB pressure sensors was thus tested. The sensor used in the overpressure tests was a multimode fiber-based sensor with a gauge length of 1.0mm, an initial cavity length of

5.67 μ m, and a fringe visibility of 49%. The sensor was calibrated to have a dynamic range of 1800psi.

Figure 8-10. Overpressure test results of the multimode SCIIB sensor

Figure 8-11. Sensor deviation of the overpressure tests

The over pressure tests were conducted at room temperatures. The sensor was first over pressured to 4000psi and kept in the pressurized chamber for one hour. After the pressure was released, the sensor was evaluated to measure pressures within its dynamic range. The same experiment was also conducted at an overpressure of 6000psi for one hour. The experimental results are shown in Figure 8-10. The deviations after the overpressures from the original calibration line are shown in

Figure 8-11. As shown in Figure 8-11, the overpressures do not show any observable effect on the sensor performance. The deviations shown in Figure 8-11 are within the range governed by the repeatability of the sensor.

8.8 Dynamic pressure measurement

To demonstrate the sensor's dynamic response, the calibrated SCIIB pressure sensors were applied for dynamic pressure measurements. The pressure signal was provided by the APP system after it was programmed to pressurize the chamber from atmosphere pressure to the preset pressure at even steps. Both the multimode sensor and the single-mode sensor were tested. The multimode sensor used was the one with a operating range of 1800psi, and the single-mode sensor had an operating range of 8500psi. The testing range for the multimode sensor was 900psi and that for single-mode sensor was 8500psi.

Figure 8-12. Dynamic pressure measurement results of the multimode sensor

The pressure increases measured by the SCIIB pressure sensors are shown in Figure 8-12 and Figure 8-13, for the multimode and single-mode fiber sensors respectively. The sampling rates of both the SCIIB sensor systems and the pressure gauge were set to one sample per second. The output of the built-in pressure gauge of the APP system is also plotted for comparison purposes. As shown in the two figures, the measurement results of both the multimode and single-mode fiber SCIIB sensors agreed very well with that of the built-in pressure gauge.

Figure 8-13. Dynamic pressure measurement results of the single-mode sensor

9.0 SCIIB pressure sensor calibration

Before the SCIIB sensor probe can be used for actual pressure measurement, it must be calibrated to relate the output ratio to the applied pressure. The sensor calibration is usually conducted by applying known pressures within its operating range. The one-to-one relation between the sensor original output and the applied pressure forms the calibration curve which can be stored in the host computer and later used to convert the sensor output to the pressure reading.

9.1 Construction of the Pressure Testing System

The sensor calibration system was constructed based on a computer-controlled high-performance pressure generator/controller manufactured by *Advanced Pressure Products, Inc.* The system configuration is shown in Figure 9-1. The pressure controller/generator can supply a hydrostatic pressure up to 20,000 psi, and the accuracy of the pressure output is 0.1% of the full scale. The construction of this system allowed us to precisely and automatically calibrate the SCIIB pressure sensor within its whole operating range. The system also allows us to test many performance characteristics of the SCIIB pressure sensor such as the linearity, hysteresis, repeatability, and dynamic range. In addition to these testing capabilities, several specially designed high temperature chambers were constructed by using heating tapes to heat the fluid and thermocouples to monitor the temperature inside. Using these chambers, the pressure sensors can also be tested at elevated temperatures.

Figure 9-1. Schematic of APP pressure sensor test system

9.2 Pressure Sensor Calibration

During the calibration process, the pressure sensor was installed inside the pressure calibration chamber. Through the computer programs, the hydrostatic pressure was applied to the sensor at the increment of 1/40 of the estimated linear range of the pressure sensor. The pressure gauge inside the APP system measured the hydrostatic pressure inside the chamber and the system saved the data as applied pressure. At the same time, the output of the SCIIB system was sampled through the A/D converter and stored into another data file. To ensure the accuracy of the calibration, the system held the pressure at each step for about 50 seconds before moving to the next step. By taking the average within the pressure holding period, the error was minimized.

Figure 9-2 shows the typical applied pressure data, and Figure 9-3 is the SCIIB output data recorded during the sensor calibration. The sensor used in the test was a single-mode fiber sensor with the gauge length of 0.5mm, the initial cavity length of 25.46 μ m, and the interference fringe visibility of 70%. Figure 9-4 plots the SCIIB output versus the applied pressure after averaging. The one-to-one relation of the applied pressure and the SCIIB output was then used to find the calibration equation through polynomial fitting. Experimental results revealed that the optimal order of the polynomial fitting was 10. Usually, the calibration curve was obtained by taking the average of several consecutive calibration data to further ensure the accuracy of calibration.

Figure 9-2. Applied pressure recorded during sensor calibration

Figure 9-3. SCIIB output ratio recorded during the sensor calibration

Figure 9-4. SCIIB pressure sensor calibration curve

10.0 Development and Testing of Optical Fibers and Sensors Suitable for Use in Moist, Elevated Temperature and Pressure Environments

10.1 Optical Fiber Testing

10.1.1 Background: Minimum Bend Radius Testing for Fibers Exposed to Water At Elevated Temperature and Pressure

In the use of optical fiber sensors for down-hole oil exploration and recovery, it will be necessary for the fiber and sensor to bend around narrow passages within the deployment column. In some cases, the radius of curvature that the fiber optic cable and sensor assembly must traverse may be very small, possibly less than five or six inches. Therefore the minimum bend radius to which the fiber can be subjected without breaking or otherwise degrading is an important consideration in design of the overall system. In this segment of the research, an experimental procedure and apparatus (as described below under experimental procedure) were developed to test the minimum bend radius that fibers treated under various conditions could survive.

In addition, it is anticipated that a protective coating may need to be applied to the fiber to prevent the penetration of water into the fiber. With this in mind, a theoretical treatment was undertaken to calculate the minimum bend radius as a function of coating thickness for several different potential coating materials. It was hoped that this would allow us to determine the proper thickness more quickly than by just using the trial and error method.

10.1.2 Procedure for Minimum Bend Radius Determination Testing

An apparatus was constructed as shown in Figure 10-1, such that two parallel metal plates attached to a micrometer could be precisely positioned to hold a fiber at a fixed radius of curvature.

Figure 10-1. Apparatus Used for Minimum Bend Radius and Time to Failure Testing

On each of the two large, movable metal plates, two small ceramic plates were bonded to form a groove that was used to hold the fibers. These ceramic plates were bonded such that the distance between them was just slightly larger than the fiber diameter. In this way, the positions of the fibers were fixed while the plates were brought closer together. The micrometer was calibrated to read zero when the two ceramic plates touched. The readings obtained from the micrometer represented the distance between the surfaces of the ceramic plates. The thickness of the ceramic plates were approximately the same thickness as the diameter of the optical fiber being tested. Therefore, the micrometer reading represented the separation distance between the inner fiber surfaces. The plates were moved at as close to a constant rate as possible during the first set of experiments. In the second set of experiments the plates were held at a constant separation distance and the time to failure was recorded.

Samples of single mode fiber were cut into lengths approximately 25 cm long. The protective polyacrylate buffer (coating) was stripped from some of the fibers and left intact on others. Fibers with the buffers stripped were placed in a stainless steel tube. The tube was filled with water and the two ends of the tube were carefully sealed. In the same manner fibers with the buffers intact were sealed with water in a stainless steel tube. The tubes were placed in an oven and heated to 200°C for specified lengths of time. The tubes were then cooled removed and opened. The water inside the tube was collected to ensure the tubes were properly sealed and the water was still present throughout the reaction time.

In general, 15 fiber breaks were measured for each experimental condition. The data points shown in each of the figures that follow represent the average of the 15 measurements.

10.1.3 Results for Minimum Bend Radius Testing

As received, single mode optical fiber with a cladding diameter of 125 microns was used as the basis for this experiment. In the first set of tests, the buffer was stripped with a razor blade. Testing of the minimum bend radius of these fibers showed that there was a large standard deviation. This was most likely due to the damage inflicted on the fiber by the razor blade. The procedure was changed to soaking the fiber in acetone to facilitate buffer removal. The acetone caused the buffer to swell and peel easily away from the fiber. The results for the minimum bend radius for the single mode fiber showed that the fiber had a average minimum bend radius of 0.045 with the buffer intact (as received) and 0.049 in. with the buffer removed by acetone. The minimum bend diameter versus exposure time at 200°C is shown in Figure 10-2.

As shown in this figure, the average minimum bend diameter for the fibers with the buffer on is approximately 0.08 in. and for the fibers with no buffer it is 0.22 in. The minimum bend diameter was the distance between the inner fiber surfaces when the fiber fractured. In both groups of fibers, the minimum bend diameter has no relation to the exposure time at 200°C. It appears that all the degradation in the fiber occurs within the first day of exposure. After the first day of exposure, subsequent days of exposure do not affect the minimum bend diameter. It is not certain why the minimum bend diameter for the fibers with buffer shows a distinct difference from those

Figure 10-2. Minimum Bend Diameter versus Exposure Time

exposed without the buffer. One likely explanation is that the buffer removal process damages the surface of the fibers. The failure of brittle ceramics is a statistical function of the probability of encountering a crack large enough produce failure at a given applied stress. The relation which governs brittle fracture in glass and ceramic materials is

$$\sigma_f = K_{IC}/(YC)^{1/2}, \quad (54)$$

where σ_f = the fracture stress, K_{IC} = fracture toughness of the material under mode I loading, Y = the crack geometry factor, and C = the crack size. As seen from this relation, the stress required for fracture to occur in the glass fiber is a function of the size of the flaws that are present. Since glass materials (and ceramics in general) are much stronger in compression than tension, the fracture almost always originates on the tensile side of the fiber (when bent). Changing the flaw population distribution along the surface of the fiber changes the stress required to fracture the fiber and therefore will affect the minimum bend radius measured. Almost certainly, the fiber with the buffer removed undergoes much more damage than the fiber with the buffer in tact just from handling the fiber to cut and insert into the tubing and possibly from the tubing wall itself.

In order to investigate the effect of the rate of application of stress on the failure bend diameter, an additional set of experiments were undertaken. The optical fibers were held at a fixed bend diameter and the time to failure measured. Figure 10-3 shows the time to failure for as-received polyacrylate-coated Corning SMF fiber versus bend diameter.

The exponential relation of the time to failure versus stress level indicates that the fiber is susceptible to stress corrosion cracking. This phenomenon, which is also referred to as fatigue in glasses, is a common occurrence. Normally, as described above, the fracture of the glass fiber occurs when the stress value reaches a critical limit dictated by the flaw population distribution. The crack propagation occurs at a velocity of approximately the speed of sound and appears for all practical purposes to occur instantaneously. If the stress is below the critical fracture stress, in certain circumstances the crack can grow at a sub-critical velocity. This is usually associated

Figure 10-3. Time to Failure versus Bend Diameter

with the presence of water in the testing environment. The exact relationship between the sub-critical crack velocity and the applied stress is not known, and in some cases is assumed to be a power function. In other cases it is assumed to be exponential in nature. In this report we will assume that the relationship follows an exponential relationship. The details of how the water present in the environment assists the propagation of the crack are not completely understood. It is generally assumed that the water reacts at the crack tip in the presence of stress to break the Si-O bond. As the Si-O bonds are successively broken the crack elongates. The rate of the reaction of the water with the Si-O depends upon the value of the stress. At higher stress values, the crack propagates more quickly and therefore the time to failure is shorter. Conversely, at lower stress values the crack propagates more slowly and time required to reach the critical crack size for the given stress level is longer.

Figure 10-4 shows the data from Figure 10-3 plotted with the y axis in log scale. As can be seen, the data appears linear when plotted in this semi-log plot. Since the diameter of the fiber is known and the radius to which the fiber is bent is known, the stress acting on the tensile surface of the fiber can be calculated. This has been done for each of the bend diameters in Figure 10-4 and the data re-plotted as a function of reciprocal stress in Figure 10-5.

As shown in this figure, the log of the time to failure is directly proportional to the reciprocal stress applied to the fiber as is predicted by the theory. In the phenomenon of stress corrosion cracking of glass materials, water is known to play a key role in the process. It is believed that the water lowers the energy required for crack propagation by breaking the Si-O (silicon-oxygen) bond as described above. This process is not completely understood. It might well be that water

Figure 10-4. Log of the Time to Failure versus Bend Diameter

Figure 10-5. Time to Failure versus Reciprocal Stress

diffuses into the glass material at the crack tip due to the high values of stress in the crack tip vicinity. It is possible that it is this diffusion of water into the crack tip vicinity that lowers the overall fracture toughness of the material. In this model, fracture would occur when the fracture toughness reaches a low enough value.

In order to further investigate this phenomenon, as-received fibers were tested along with fibers soaked in water at room temperature for 30 minutes. These data are shown in Figure 10-6.

Figure 10-6. Average Time to Failure for Optical Fiber versus Bend Diameter

After only 30 minutes of soaking, the fiber shows a significant reduction in the time to failure for the single mode fiber (SMF) with the buffer intact. Samples of the new single mode fiber were also soaked in acetone for 30 minutes and an increase in the time to failure was observed. In order to investigate whether these processes were reversible, the SMF fibers were soaked in water for 30 minutes then in acetone for 30 minutes. The acetone soak completely negates the effect of the water soaking. Conversely, fibers soaked in acetone for 30 minutes then in water for 30 minutes show the water soaking completely negates the affect of the acetone soaking. All of these data are shown in Figure 6. These data clearly show that water has a detrimental effect on the time to failure of SMF fiber. The new unsoaked fiber that was tested had most likely absorbed water from the atmosphere. Removal of this water during the acetone soak is responsible for the increase in the time to failure of the fibers as compared to the "as-received" condition. The value for the fibers soaked in water for 30 minutes and then in acetone for thirty minutes held at a bend diameter of 0.054 inches is unusually high. It is suspected that the reason for this is solely due to measurement scatter. In that group of 15 fibers that were tested, one fiber exhibited a much longer time to failure than the other fibers in that group. If the reading for that fiber is eliminated, the data for that set would lie almost exactly on top of the data for the fibers soaked in acetone for 30 minutes (no water treatment).

In another set of experiments, samples of the SMF fiber were soaked in water for 24 hrs, then removed and allowed to stand in air for various periods of time before testing. The results are shown in Figure 10-7. After soaking in water for 24 hrs, the time to failure was very short (less than 1 second). As time progressed, however, the time to failure steadily increased until it reached the same level as that of the new fibers. This is most likely due to the loss of water from the fiber to the air. This result clearly shows that the process of degradation of the fiber due to

exposure by water is completely reversible by allowing the fiber to lose the water by standing for a period of time in air. No permanent effects are observed due to the water treatment.

Figure 10-7. Time to Failure versus Time after Exposure

A theoretical treatment was undertaken to calculate the minimum bend radius as a function of coating thickness for several different materials. The data from these calculations is shown in Figure 10-8. The calculation is based on a 125 micron outer diameter optical fiber coated with various thickness and types of materials.

Figure 10-8. Calculated Minimum Bend Radius versus Coating Thickness for Various Coating Materials

The minimum bend radius was determined as that point at which 0.002% plastic strain would occur in the metal coating. From the curves, it can be seen that an upper limit of about 10 microns or so is about the maximum thickness the coating should be (depending of course upon the choice of material used).

10.2. Background: Testing of Fibers Exposed to Water At Elevated Temperature and Pressure

The goal of this segment of the research program was to evaluate the performance of the optical fiber which will be used to connect the sensor head to the outside world (above ground). Data from Chevron has indicated that penetration of water into optical fibers in the down-hole environment has proved to be detrimental to the life of the fiber. In order to protect the fiber from water, a series of experiments was performed to develop a suitable coating to protect the optical fiber. In order to test the effects of water at elevated temperature and pressure, a special apparatus was constructed as described in the experimental procedure section below. The fibers tested in these experiments were subjected to much higher temperatures than would normally be seen in the down-hole environment (approximately 100% higher, 300°C test temperature as compared to 150°C expected maximum operating temperature). The effect of the increased testing temperature on the rate of diffusion of water into the silica fiber is expected to be exponential as described in the results and discussion section. Since the rate of penetration of water into the unprotected fibers was significant, several methods of protecting the fiber were tested in the experimental setup as well.

10.2.1 Experimental Procedure for Fiber Testing in Water at Elevated Temperature and Pressure

Two methods for protection of the optical fiber were selected for testing initially. These employed stainless steel needle tubing and carbon coating. In the case of stainless steel needle tubing, tubing approximately 508 micron OD and 292 micron ID was used. The polyacrylate-coated fiber was inserted into the stainless steel tubing which was filled with water. This fiber and tubing were inserted into another stainless steel tube approximately one quarter inch in diameter such that the needle tubing extended beyond the end of the tubing fittings. The fittings had been predrilled with a small hole just slightly larger than the diameter of the needle tubing. The needle tubing was sealed to the fitting using Miller-Stephenson 907 epoxy. This assembly was in turn inserted into a tube furnace heated at 300°C, such that the ends of the stainless steel tube, which were epoxied, stuck out of the ends of the furnace. The ends of the optical fibers were connected to a white light source and to an optical spectral analyzer respectively. Several other channels were prepared in the same way. In the second channel, a Spectran carbon/polyimide coated fiber was sealed in water in the stainless steel tubing. In the third channel, an as-received polyacrylate-coated multimode fiber without any additional protection was sealed. The fourth channel was used as a reference channel. A fiber was connected from the white light source to the optical spectrum analyzer directly without passing through the furnace. This was used as a reference to compensate for any changes in optical power from the white light source that might occur. All of the fibers were connected to the same white light source through a series of couplers such that once the connections were made they were not disturbed throughout

the entire testing process. The apparatus is shown schematically in Figure 10-9. The pressure developed in the tubing can be determined from the steam tables. At 300°C the pressure inside the stainless steel tubing is 1440 psi.

10.2.2 Results of Testing the Performance of the Optical Fiber in Water at Elevated Temperature and Pressure

Figure 10-10 shows the absorption in decibels (dB) versus time in hours for the fibers immersed in water and heated to 300°C. As can be seen in this figure, the as-received fiber (without any protection) labeled "water" shows a relatively high absorption rate of water. In comparison, the carbon/polyimide coated fiber, labeled Spect 2, shows very low water absorption tendency. It must be pointed out that 300°C represents a much higher temperature than the fiber would normally experience in the down-hole environment. Normally the fiber will experience temperatures less than 200°C. The penetration rate of water into the fiber is assumed to be diffusion controlled. Water at the surface of the fiber diffuses into the fiber due to the concentration difference between the surface and the interior. If the process is diffusion controlled, the flux of water into the fiber will be proportional to the diffusivity of water in the silica glass multiplied by the chemical potential gradient. If we let J = the flux of water, D = the diffusivity and $\nabla\mu$ = the chemical potential gradient then

$$J = D\nabla\mu. \quad (55)$$

The chemical potential is defined as the partial molar free energy

$$\mu = \partial G / \partial n_i, \quad (56)$$

where G = free energy of the system, and n_i = number of moles of component i . For diffusion only in one dimension, for example the x direction. Assuming that the chemical potential gradient can be approximated by the concentration gradient of the diffusing species, the equation simplifies to

$$J = D \partial C_i / \partial x, \quad (57)$$

which is the familiar form of Fick's first law for diffusion.

Since diffusion is a thermally activated process, the diffusivity can be represented as

$$D = D_0 \exp(-Q/RT), \quad (58)$$

where Q = activation energy for the rate controlling process, R = the ideal gas constant, D_0 = the pre-exponential term and T = the temperature. As seen from this relation, the diffusivity, and likewise the flux, will be exponentially dependent upon the temperature. Therefore, the penetration rate of water into the fiber at 300°C will be exponentially higher than the rate at 200°C. So the testing temperature of 300°C represents a significant accelerating factor in the testing.

Figure 10-10. OH absorption versus Time for Fibers Immersed in Water at 200°C

The fiber within the needle tubing labeled as "W/T" (water with tubing) has shown no detectable change in the absorption due to water. This is a remarkably good result and shows the stainless steel needle tubing can provide excellent protection against water penetration.

10.3 Development of Carbon Coated Sensors

As mentioned previously, due to the outstanding results for protection against water penetration obtained for carbon coated and stainless steel needle tubing protected fibers, both metal coatings and carbon coatings are being investigated to protect the sensor head. In this section, the results of the carbon coating development work will be presented. The coating method employed to deposit amorphous carbon onto the sensor head is laser ablation deposition. In this technique, a krypton-fluoride laser is directed through a series of mirrors and windows at a rotating carbon target in a vacuum chamber, which is pumped down to 10^{-6} torr. After stabilizing at this vacuum for a short period of time, oxygen is introduced into the chamber. The vacuum is stabilized at 10^{-4} torr. At this point the shutter to the laser beam is opened and the laser beam admitted to the target. A computer-controlled pulse firing sequence is initiated. The carbon is ablated from the surface with each pulse of the laser and deposits on the sample. The pulse count for samples coated to date has been 4000. After coating, the laser beam shutter is closed and the chamber is repressurized. The chamber cover is then opened and the samples removed.

Figure 10-11 shows an SEM micrograph the fracture surface of a sensor coated using the laser ablation technique. As shown in this figure, the coating appears to be very uniformly distributed around the surface of the fused silica glass.

Figure 10-11. SEM Micrograph of the Fracture Surface of an Optical Fiber Coated with Carbon by Laser Ablation

It should be noted that the sample in the SEM micrograph shown above is rotated about 10 degrees toward the viewer. The surface of the coating appears smooth and very uniform. The carbon coating thickness is approximately 1 micron. The fiber shown here is from the reflecting end of a sensor.

The entire sensor assembly was examined by optical microscopy as well. In transmitted light, the entire sensor system seemed uniformly coated. No pits, bubbles or obvious imperfections were observed. A Spectran carbon/polyimide coated fiber was used as the lead-in fiber in this sensor. The fiber was carbon-coated all over, except for the lead-in end, where the carbon coating was removed by soaking in hot sulfuric acid. After sensor bonding (fiber is bonded inside a fused silica tube), a short section of the fiber, which had been stripped, remained outside the tube. The laser ablation coating process not only coated the sensor head uniformly, but also coated the portion of the fiber that had been stripped during the sensor fabrication.

Experimentation has been conducted to develop a method to overcoat the carbon coated sensors with a polyimide coating. Several sensors have been successfully coated with the polyimide material and cured. These sensors have been sealed in the high temperature, high pressure testing apparatus and are currently undergoing long term stability testing.

11.0 Testing the Performance of the Optical Fiber Sensor Head in Water at Elevated Temperature and Pressure

In addition to protecting the fiber from water, the sensor head must also be protected. In this segment of the research, a suitable protection for the sensor head portion will be developed. Based on the exciting results obtained in the fiber protection testing segment for the carbon coated fibers and the stainless steel tubing, metal coatings and carbon coatings have been chosen for study for sensor head protection.

In order to evaluate the stability of the signal processing system, the system was connected to an optical fiber with the endface cleaved such that the reflected signal could be monitored. It should be noted that in this test the optical fiber was not connected to a sensor. In this test the ratio of the output of the narrow band as compared to the broad band is plotted versus the time in minutes. The results of this set of tests is shown in Figure 11-1. The standard deviation for ratio of the narrow band to the broad band for this set of data is 0.0000498. Therefore, over the time frame tested, the system is very stable.

Figure 11-1. Results of Stability Testing of Signal Processing System – No Sensor Attached

Figure 11-2. Results of Stability Testing of Signal Processing System, with Sensor held at 300°C.

After testing the stability of the signal processing system without the sensor attached, the stability of the entire system with a sensor attached was evaluated. Since the down-hole oil environment will require the sensor to withstand elevated temperatures, the stability of the entire system was evaluated with the sensor heated to 300°C in air. The results of this testing are shown in Figure 11-2. The standard deviation of this set of data was 0.0004355. The maximum drift is 0.38% compared with the mean value.

In order to protect the sensor head from penetration by water, protective coatings are being developed. The first metal to be studied was gold. Gold coatings were applied to the sensor head by a sputter coater used to coat scanning electron microscope samples. Figure 11-3 shows the results of the stability testing for a gold-coated sensor held at 205°C for two weeks in air. The standard deviation was calculated to be 0.0014.

In the down-hole oil environment, the sensor will be subjected to simultaneous application of elevated temperature and pressure in an environment containing water. In order to evaluate the effects of such a combination of variables upon the long term stability of the sensor, a series of experiments were performed. In the first set of experiments an uncoated sensor was placed in the APP high pressure calibration system. The system was heated to 200°C. The SCIB output pressure as a function of the applied pressure was measured once per day. The results are shown in Figure 11-4 a and b.

Figure 11-3. Results of Stability Testing of Signal Processing System – Gold Coated Sensor Held at 205°C

Figure 11-4 a. Measured Pressure versus Applied Pressure as a Function of Exposure Time for an Uncoated sensor

Figure 11-4 b. Measured Pressure versus Applied Pressure as a Function of Exposure Time for an Uncoated sensor continued

As can be seen in this figure, the curve shifts as a function of exposure to the high temperature, high pressure environment. The pressurizing fluid that was used in these experiments was water. It is believed that the shift in the curves represents the change in the physical dimensions of the sensor due to penetration of water molecules into the glass structure. The magnitude of the change from one day to the next day becomes smaller as time progresses. It is not certain whether the sensor is saturated with water, preventing further significant changes in sensor reading or whether the shift will progress. Further work will be done to clarify this issue.

In order to prevent water penetration into the sensor head, various coatings are being investigated. Gold was chosen as the first coating material to be studied. The procedure described above was repeated with a sensor coated with gold. The gold coating was applied with a gold sputtering system. The gold was applied only to the sensor head and is believed to be approximately a few hundred nanometers thick based on previous experience with using the sputter coater to coat SEM samples. The data obtained in this fashion is shown in Figure 11-5a and b.

As shown in this figure, the gold-coated sensor exhibits a shift in the curve similar to the uncoated sensor, but larger in magnitude. The gold coating applied to the sensor did not adhere well. This is a common problem in the mirror industry. In order to allow the gold to stick to the substrate more strongly, a chromium layer is first applied to the glass before the gold is applied. In the current gold sputtering system used in these experiments, the option to put down a layer of chromium before the gold is applied is not available. In a new sputtering system being purchase by the Photonics group, deposition of chromium first followed by gold deposition will be possible.

Figure 11-5 a. Measured Pressure versus Applied Pressure as a Function of Exposure Time for an Gold Coated sensor

Figure 11-5 b. Measured Pressure versus Applied Pressure as a Function of Exposure Time for a Gold Coated sensor

Figure 11-6 shows the change in sensor output as a function of exposure time for both the gold-coated and uncoated sensor.

Figure 11-6. Pressure Calibration Difference Between First and Following Days versus Date for a gold coated and an uncoated sensor

The curves shown in this figure represent the variation between the pressure reading (in psi) as measured by the SCIIB system, at 3000 psi applied pressure, on the first day compared to the day being measured. For example, the pressure reading on day 5 from the SCIIB system at 3000 psi applied pressure minus the pressure reading from the SCIIB system on day 1 at 3000 psi applied pressure would become the value plotted for day 5. It can be seen from this figure that the readings for both the gold coated and the uncoated sensors show a positive trend. The magnitude of the slope for a gold-coated sensor is approximately twice the magnitude of the slope for the uncoated sensor. It is suspected that the increase in slope for both the gold-coated and uncoated sensor is due to penetration of water into the sensor.

Figures 11-7a and b and 11-8a and b show a second set of data for the variation in calibration for a gold coated and an uncoated sensor. The data appear to be very consistent with the data shown in Figures 11-4a through 11-5b. The data for the pressure calibration variation versus number of days of exposure is shown in Figure 11-9 and shows a similar relation to that shown in figure 11-6 for the previous set of data.

Figure 17 a. Measured Pressure versus Applied Pressure as a Function of Exposure Time for an uncoated sensor

Figure 11-7 b. Measured Pressure versus Applied Pressure as a Function of Exposure Time for an Uncoated sensor continued

Figure 11-8 a. Measured Pressure versus Applied Pressure as a Function of Exposure Time for an Uncoated sensor

Figure 11-8 b. Measured Pressure versus Applied Pressure as a Function of Exposure Time for an Uncoated sensor continued

Figure 11-9. Pressure Calibration Difference Between First and Following Days versus Date for a gold coated and an uncoated sensor

Figure 11-10. SCIIB Output Versus Applied Pressure and as a Function of Different Fiber Pigtail Polarization States

Figure 11-10 shows the variation in the SCIIB output ratio versus applied pressure for different states of polarization of the fiber pigtail. In this set of experiments, the fiber was rotated to various degrees while the readings were being acquired. The average system polarization error was calculated to be 1.12%

Figure 11-11 shows the variation in SCIIB output versus the applied pressure for different splicing losses. Initially, the system was spliced with a fusion splicer and the readings taken. The splice was then broken and respliced and the readings taken again. In each case the loss due to splicing as measured by the fusion splicer is noted on each curve on the graph.

Figure 11-11. Effect of Fusion Splice Loss on the SCIIB Output

In an attempt to improve the system stability, a second system was constructed. Calibration curve changes for this system for the fiber pigtail polarization state had an average polarization error of about 0.23%~0.787% as shown in Figure 11-12.

Figure 11-13 shows the SCIIB output versus applied pressure for different splice losses for the improved system. The splice loss repeatability in the new system has dropped to approximately 0.5%

Figure 11-12. SCIIB Output Versus Applied Pressure and as a Function of Different Fiber Pigtail Polarization States for Improved System

Figure 11-13. Effect of Fusion Splice Loss on the SCIIB Output for Improved System