Invited Paper

SCIIB Pressure Sensors for Oil Extraction Applications

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ABSTRACT

Efficient and complete recovery of petroleum reserves from existing oil wells has proven difficult due to a lack of robust instrumentation that can monitor processes in the downhole environment. Commercially available sensors for measurement of pressure, temperature, and fluid flow exhibit shortened lifetimes in the harsh downhole conditions, which are characterized by high pressures (up to 20 kpsi), temperatures up to 250°C, and exposure to chemically reactive fluids. Development of robust sensors that deliver continuous, real-time data on reservoir performance and petroleum flow pathways will facilitate application of advanced recovery technologies, including horizontal and multi-lateral wells. We describe the development and fabrication of pressure, temperature, and flow sensors designed for the downhole environment, based on the Self-Calibrated Interferometric/Intensity-Based (SCIIB) configuration, which combines the high sensitivity of interferometric sensors with the high-speed of intensity-based sensors. By splitting the output of a Fabry-Perot sensor into two channels with differing coherence, unwanted perturbations, such as source power fluctuations and variations in fiber loss, may be compensated. Results of laboratory tests of prototype sensors demonstrate excellent resolution and accuracy.

Keywords: fiber optic sensors; harsh environment sensors; interferometric sensors

1. INTRODUCTION

Despite advances in the technology of oil recovery, as much as 66% of the oil in known reservoirs remains unrecovered following primary, secondary, and even tertiary attempts at recovery.[1] In large part, this results because the remaining oil is found in fragmented, non-contiguous pockets. In response to this situation, the oil industry has applied new techniques to exploit such spatially dispersed reserves, including horizontal wells and steam floods. In the latter technique, boreholes are drilled in the proximity of the reserves, and steam is injected into the boreholes to flood the reservoir, and hopefully drive the remaining oil to a producing well.

These new methods have not realized their full potential for improved oil recovery due to limitations in acquisition of data that could be used for optimization of the oil extraction. Sensors that are available for characterization of the physical parameters of the recovery process in the downhole environment have not demonstrated sufficient reliability to be practical for this application. The downhole environment is characterized by moderate temperatures (to 250°C), high pressures (to 20,000 psi), and corrosive fluids (water, hydrocarbons, and sulfides). Robust sensors that are easily deployed, that can survive the harsh environment, and that are insensitive to undesired perturbations such as temperature changes.

We describe preliminary efforts in the development of ruggedized sensors based on optical fiber technology for in-situ characterization of downhole conditions, to permit optimized oil recovery and to enable intelligent completions. Research at our laboratory is proceeding in two directions: ruggedization of sensors and cables

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based on optical fibers, and development of self-calibrated sensor methods for measurement of pressure, temperature, and flow downhole. In this paper, we describe initial results in the development of a self-calibrated pressure sensor for use in a downhole environment.

2. PRINCIPLES OF OPERATION

The pressure sensor investigated for use in downhole instrumentation was based on the Self-Calibrated Interferometric/Intensity-Based (SCIIB) fiber optic sensor invented at Virginia Tech.[2] The SCIIB design embodies three innovations that make it well suited for downhole measurements. First, an optical technique is used to provide self-calibration of the sensor, rendering it insensitive to undesired perturbations, such as fluctuation in source power or cable loss. Secondly, the mechanical design of the sensor is adjusted so that the output (intensity) of the sensor is a linear function of the measurand, simplifying the processing of the sensor output. Thirdly, the sensor probe is constructed of glass element, thermally fused together, thereby eliminating organic adhesives, which may lead to viscoelastic creep in the sensor.

The principals of operation of the SCIIB pressure sensor are illustrated in Figure 1. An optical source, such as a superluminescent diode, with a broad spectral output is connected through a 2x2 coupler to a sensor, which is formed by aligning the input fiber with a short reflector fiber, using a glass capillary tube to ensure that the axes of the two fibers are collinear. The adjacent ends of the two fibers are cleaved or polished, so that a Fabry-Perot cavity is formed by the fiber ends. Two Fresnel reflections, R1 and R2 in the figure, are generated due to the difference in refractive indices of the glass and the air, and are guided back though the input fiber and the coupler to an optoelectronic subsystem where the optical signal is processed. In this subsystem, the optical signal is split into two paths: in one path, the full spectral width of the source is preserved, and in the second, the signal is optically filtered to reduce the spectral width.

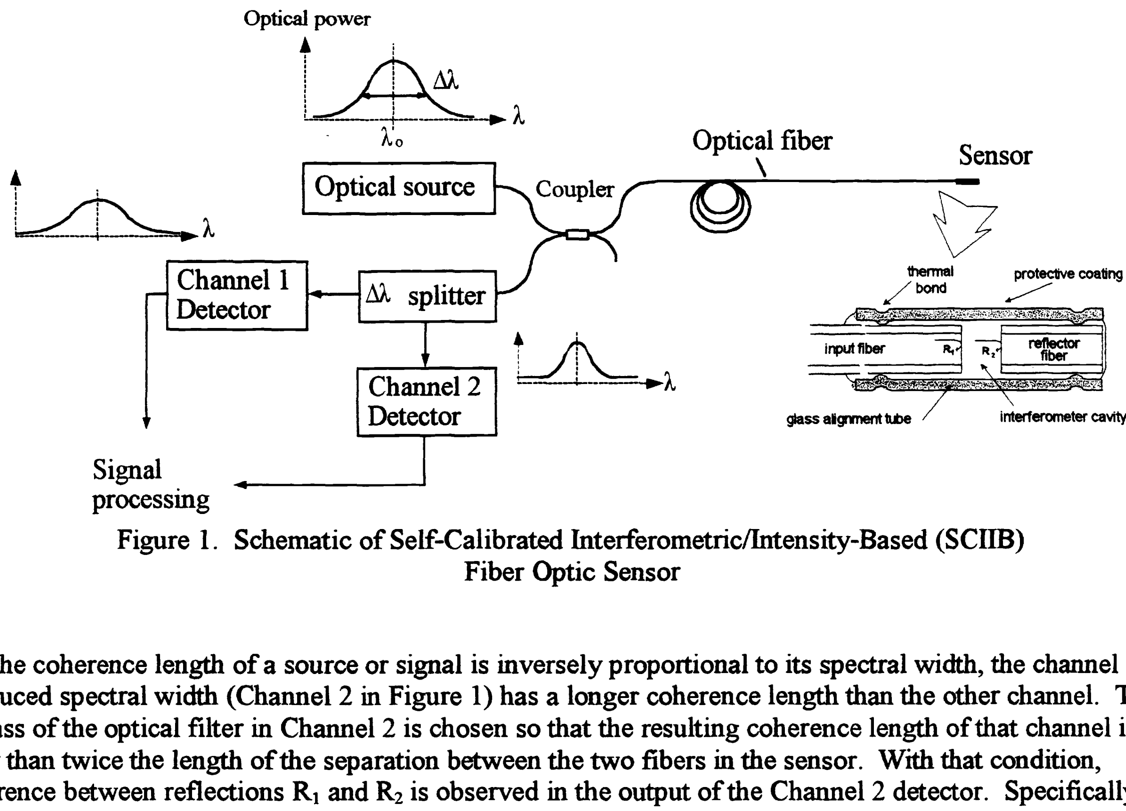

Figure 1. Schematic of Self-Calibrated Interferometric/Intensity-Based (SCIIB) Fiber Optic Sensor

Since the coherence length of a source or signal is inversely proportional to its spectral width, the channel with the reduced spectral width (Channel 2 in Figure 1) has a longer coherence length than the other channel. The bandpass of the optical filter in Channel 2 is chosen so that the resulting coherence length of that channel is greater than twice the length of the separation between the two fibers in the sensor. With that condition, interference between reflections R_1 and R_2 is observed in the output of the Channel 2 detector. Specifically, the output will vary sinusoidally with a change in the gap separating the sensor fibers. This change in the intensity of the light incident on the Channel 2 detector can be used to measure changes in the length of the air gap that may occur due to physical effects such as pressure.

To simplify the processing of the output signal, the construction of the sensor probe is adjusted in order to limit the output of Channel 2 to the quasi-linear region of the sensor output. Figure 2 illustrates the variation of optical intensity that results from the interference of reflections R_1 and R_2 when the gap separating the input fiber and the reflector fiber are increased. By choosing appropriate values for the wall thickness of the capillary tube, the length of the tube, and the modulus of elasticity of the tube, the output of the sensor over the desired operating range of the sensor can be constrained to fall within the region denoted by the blue line in Figure 2. The sensor output may then be interpreted as a linear function of the measurand; in this way, the simple signal processing of an intensity-based fiber optic sensor is achieved, with the high sensitivity characteristic of interferometric sensors.

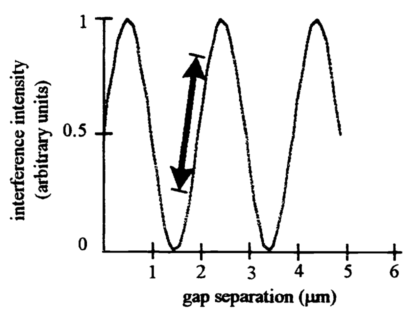

Figure 2. Output of Fabry-Perot interferometer,
with quasi-linear output of sensor indicated by bold line.

If the output of the sensor is interpreted as a linear change in the output of Channel 2, then undesired physical effects that may change the intensity of light into the optoelectronic subsystem, such as fluctuations in the output power of the optical source or changes in the attenuation of the optical cable (due to bends, for instance) might be misinterpreted as a change in the parameter being measured. The second signal path in the optoelectonic subsystem (Channel 1 in Figure 1) is used to compensate for these undesired effects. Since light incident on the detector in that channel is unfiltered, it has that full spectral width of the source, and therefore has a short coherence length. During construction of the sensor probe, the gap between the two fibers is adjusted to ensure that it is longer than one half of the coherence length of Channel 1. In this way, the output of Channel 1 does not exhibit interference between the two reflections from the sensor; it is, however, proportional to the sum of the intensities of the two reflections. Changes in the source output power or in the cable attenuation or in connector loss are common mode to both channels, while the interference effects are exhibited only in Channel 2. Therefore, by taking the ratio of the output of Channel 2 to Channel 1, the undesired loss factors are canceled out, leaving only the factors describing the interference effects, which give the desired measurement.

Figure 2 plots the results of analysis predicting differences between the two channels in the optoelectronic subsystem. In this analysis, a source with a peak wavelength of 850 nm and a full width half maximum spectral width of 70 nm is assumed. In the top plot, interference effects are seen to vanish in the reference channel (Channel 1) for sensor air gaps greater than 5 μm. In the bottom plot, it was assumed that the sensor channel (Channel 2) was filtered to a width of 10 nm. As the plot shows, interference effects are observable beyond 5 μm.

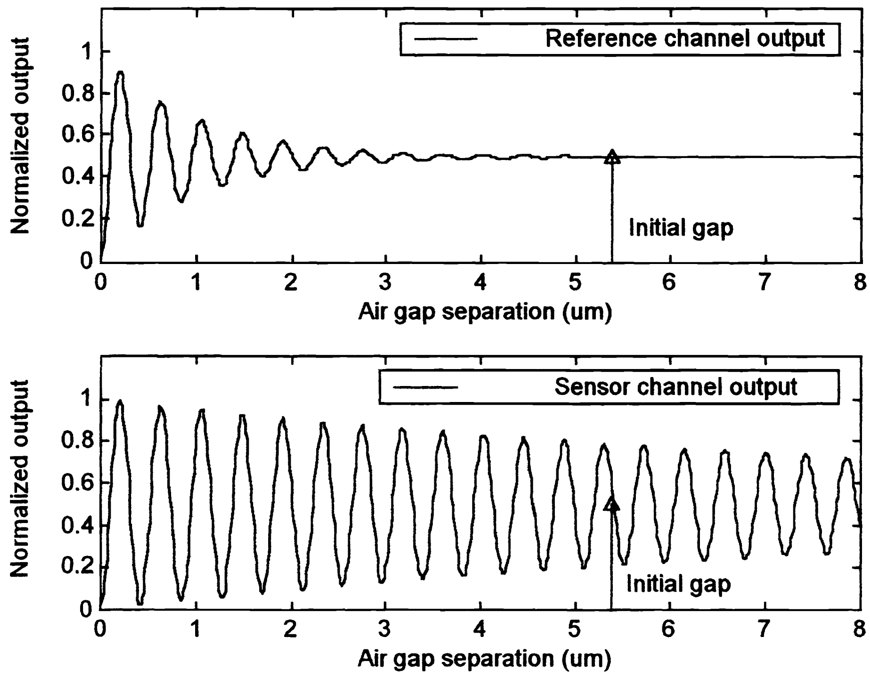

Figure 3. Normalized output of SCIIB reference channel (Channel 1 in Figure 1) and sensor channel (Channel 2 in Figure 1), showing effect of reduced coherence length on the reference channel.

3. EXPERIMENTAL DEMONSTRATION

In order to design sensors that can respond to changes in applied hydrostatic pressures, the principles of mechanics were applied to derive an analytical expression predicting the change in the cavity length with applied pressure. The change ΔL in air gap separation as a result of an applied pressure p is found to be

$$\Delta L = \frac{Lpr_o^2}{E(r_o^2 - r_i^2)}(1-2\mu) \tag{1}$$

where

p is the applied pressure,
μ is the Poisson's ratio of the glass, and
E is the Young's modulus of the glass.

The parameters L, r_0, and r_I relate to the geometry of the sensor construction, and are illustrated in Figure 4.

To test the analytical predictions, a prototype sensor was constructed using a one centimeter long glass capillary tube to align two 62.5/125 μm multimode fibers. The capillary tube had an inside diameter of 130 μm, and an outside diameter of 365 μm. The tube was bonded to the fibers using the output of a carbon dioxide laser to fuse the glass. The input fiber was connected to a laser/coupler/photodiode system, so that the change in the air gap

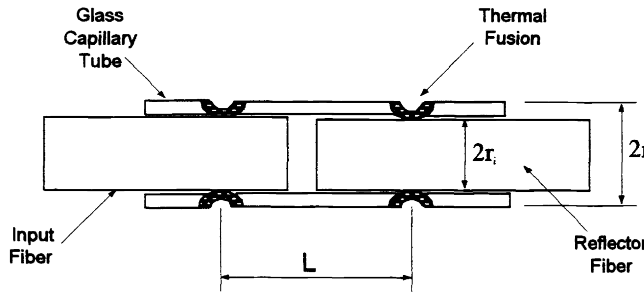

Figure 4. Schematic illustrating geometry of SCIIB pressure sensor.

length could be determined within 0.1 μm by counting interferometric fringes. The sensor was fitted inside a pressure vessel connected to a deadweight pressure tester using a pressure feedthrough fitting. The pressure vessel was pressurized to 5000 psi in steps of 500 psi through the addition of weights to the deadweight tester. As Figure 5 confirms, the results obtained experimentally agree well with the predictions obtained analytically. The slight deviation at high pressure are thought to result from the lack of a precise value for the Young's modulus of the glass tube; instead, a value taken from a table of material properties was used.

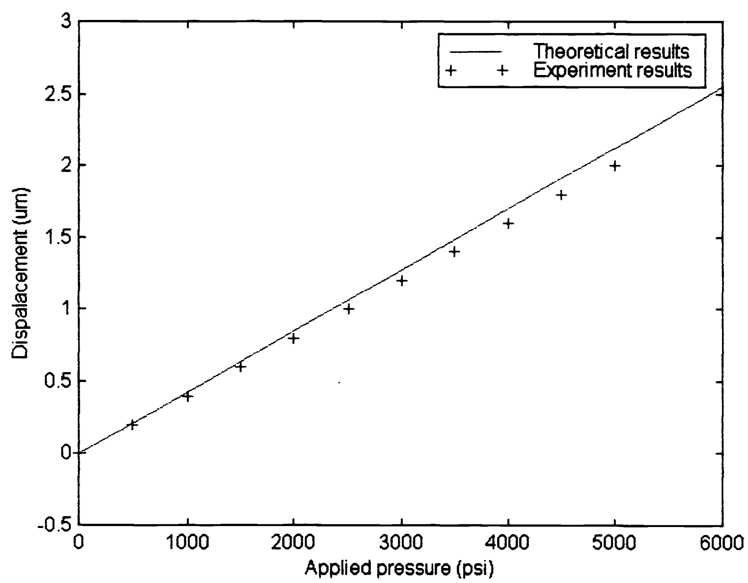

Figure 5. Comparison of experimental results with analytically predicted results for SCIIB pressure sensor.

The cross-sensitivity of the SCIIB pressure sensor to temperature changes was evaluated by fabricating a new sensor using 62.5/125 μm fiber aligned and fused to a 130/365 μm (ID/OD) glass tube. The separation of the two points at which the tube was fused was 630 μm. The input fiber of the sensor was connected to a two channel SCIIB optoelectronic subsystem similar to the one depicted in Figure 1. The sensor probe was fitted into the pressure vessel, which in turn was wrapped with electrical heating tape and instrumented with a thermocouple to monitor the temperature. The pressure was varied from 0 to 2000 psi in steps of 100 psi, as the temperature was held constant at 50°C. Then the temperature was increased to 100°C, and after the temperature was stabilized, the pressure was again varied from 0 to 2000 psi. This test was again repeated at temperatures of 145°C and 196°C. As the results in Figure 6 indicate, the measurement of pressure was repeatable and largely insensitive to the temperature changes. The cross-sensitivity to temperature changes was measured from these results to be 0.04% $°C^{-1}$ over the full scale.

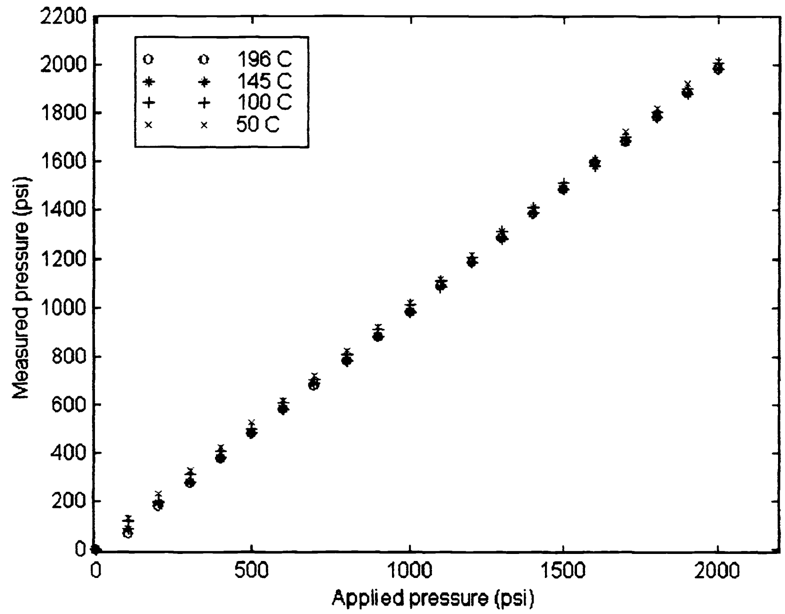

Figure 6. Output of SCIIB pressure sensor for applied pressure at different temperatures.

Finally, the self-calibration function of the prototype SCIIB pressure sensor was evaluated. Fot this test, a 62.5/125 µm multimode fiber was connected to the two channel SCIIB optoelectronic subsystem. The fiber was cleaved at the end, in order to generate a Fresnel reflection of the light incident at the end. A sensor cavity was not formed at the end of the fiber, in order to eliminate interference effects that could complicate interpretation of the test results. The input fiber was bent around a mandrel, in order to generate successively smaller loops that would increase the bend loss in the fiber. Ideally, the output of the sensor should be independent of bend loss in the fiber. Since interference effects are absent in this test, the desired result is that the output of the SCIIB system is constant despite increasing bend loss.

Figure 7 plots the results of the test in which the loss in the fiber is increased by reducing the diameter of the fiber bend. The amount of fiber loss was determined by measuring the voltage V_{bent} output by the reference channel when the fiber was bent. This measurement was divided by the output of the reference channel $V_{straight}$ recorded before the fiber was bent, and subtracted from a value of 1 to describe the loss as a normalized value, where

$$normalized\ fiber\ loss = 1 - \frac{V_{bent}}{V_{straight}}. \qquad (2)$$

The output of the SCIIB system, found by taking the ratio of the signal channel to the reference channel, was plotted as a function of the normalized fiber loss as the loss was increased from zero to 0.5 (3dB). The results in Figure 9 indicate that the SCIIB system is very effective in rejecting changes in optical power that are common mode to both the reference and sensor channels.

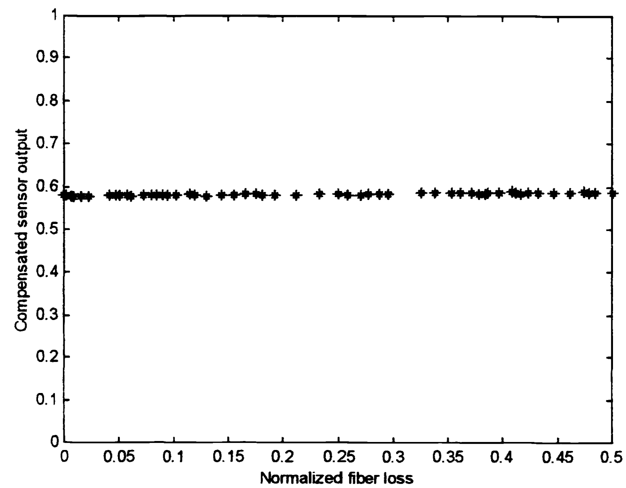

Figure 7. Plot of SCIIB system output as fiber loss was increased up to 3 dB through bending of input fiber.

4. CONCLUSIONS

Pressure sensors based on a novel fiber optic sensor configuration, the Self-Calibrated Interferometric/Intensity-Based (SCIIB) sensor, were designed for downhole instrumentation of oil wells. Prototype sensors were constructed and tested to confirm the analytically predicted operation of the over a pressure range from 0 to 5000 psi. Testing of the sensor over a range from 0 to 2000 psi while the temperature was varied from 50°C to 196°C showed that the sensor exhibits a very low cross-sensitivity to temperature changes. An experiment to investigate the self-calibration function of the SCIIB system demonstrated that the system is insensitive to changes in loss induced by bends in the fiber.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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