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INTERFEROMETRIC HIGH-PRESSURE SENSOR

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DECEMBER 1988

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This work proved the feasibility of an interferometric, high-pressure sensor. A pressure measurement system based on a birefringent, compact, Fabry-Perot etalon was selected and designed. The temperature response of the reflectivity of the etalon was calibrated; a 1°C change in temperature was equivalent to a 1000 psi pressure change. Efficient coupling of the key components was demonstrated using a monolithic, single-frequency, diode-pumped ring laser (developed at Lightwave Electronics Corp. based on Stanford University research), a single-mode optical fiber, and a sapphire etalon. Successful experimental results demonstrate that an optical pressure transducer can be made that has the properties of compactness, wide pressure range, immunity to electro-magnetic interference, and low cost.

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The view, opinions, and findings contained in this report are those of the authors and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

Introduction

Many government applications and industrial processes require pressure measurement in high pressure environments. An all-optical measurement system offers the potential for a rugged and compact sensor that is immune from electrical and magnetic interference. The capability to measure higher pressures in extreme environments may result from an optical system of this type, as well as the fabrication of inexpensive detector heads. This could lead to a more general line of interferometric pressure sensors. New diode-pumped laser sources now make this even more attractive. Fiber coupling with a single fiber allows access to pressure chambers with extremely high pressures. The key technologies involved with the optical detection system studied are the etalon, the stable laser source, and the optical fiber.

Technical Background

The research performed under this Phase I feasibility study investigated the application of a solid Fabry-Perot etalon to pressure measurement. An etalon is an interferometer composed of two partially mirrored surfaces, forming an optical cavity, flanking an optically transmissive region [1]. The reflection or transmission of this interferometer varies with (1) the wavelength of the light, (2) the angle of incidence of the light upon the etalon, (3) the reflectivity of the mirrored etalon surfaces, (4) the losses in the etalon cavity, and (5) the optical path length through the transmissive region. The first four parameters only hinder the accurate measurement of pressure. Therefore, the research focused on the pressure dependence of the optical path length, and ways to isolate this dependence from the other four variables.

Lightwave Electronics Corporation is now building and selling single-frequency diode-pumped solid state lasers, making it possible to test sensitive interferometric measurements that previously would have been uneconomical or impossible. This laser is unique in its ability to maintain single frequency operation independent of power. Referred to as a Monolithic Isolated Single-mode End-pumped Ring laser, or "MISER," it is based on a Stanford University ring laser patent to which we have rights.

A stable design for this interferometric measurement system was developed during the Phase I research, in which the components are all epoxied together. This allows the optical interface losses to be fixed, and the incident angle to be set using a special lens glued to the etalon. The use of lenses is commonplace when dealing with laser light, and the existence of Selfoc lenses lends a flexibility previously unattainable. The light bending properties of standard spherical lenses are a result of the curved interfaces between media of different indices of refraction. Selfoc lenses are small cylindrically shaped lenses with the cylinder axis along the optical axis. The index of refraction decreases as the square of the radial distance from the optical axis [2]. This parabolic index of refraction gives a Selfoc lens the same optical properties as a standard lens, but with flat end surfaces. This allows mounting of a Selfoc lens, for example, directly on the end of an optical fiber, fixing the angle of incidence of light focussed into a fiber or collimated out of the fiber onto an etalon. Only the material on the other side of the etalon gets exposed to the pressure chamber. Light travels sinusoidally through the graded index material, and so the length of the lens determines the image on the end surface. The exiting light can be collimated, focussed, or divergent depending on the pitch length of the lens. Collimated laser light can be focussed into a fiber through a lens only a few millimeters long. Selfoc lenses are available to closely match the numerical aperture (NA) of a single-mode fiber. The NA of a fiber is defined as the sine of the largest angle an incident ray can have for total internal reflectance in the core [3]. The use of Selfoc lenses to eliminate the problem of misalignment between the lens, fiber, and etalon during a pressure change or other source of vibration was examined in this Phase I study.

The change in an etalon's reflectivity indicates that the optical path, and thus the pressure exerted on the etalon, is varying. However, the direction of the pressure change is unknown. For this information, a second etalon of a slightly different path length, or one birefringent etalon, would be useful. A birefringent material has two different indices of refraction, depending on the polarization of light travelling through the material [1]. Therefore, light propagates at different speeds through a birefringent crystal; faster polarized along one axis than the other. This existence of a fast and slow axis leads to different optical thicknesses for different polarizations. The optical path length is the product of the index of refraction times the actual thickness of the material. Two polarizations of light reflected from one birefringent etalon give equivalent information as light reflected from two regular etalons of slightly different lengths. This birefringence was studied and exploited as an aid to pressure measurement.

Objectives

The ultimate objective of this SBIR program is the development of an interferometric high-pressure sensor for use in physically or electrically harsh environments. The measurement system should meet the following specifications:

(1) pressure range 0 to 150,000 psi*
(2) accuracy 5,000 psi
(3) temporal resolution 0.1 millisecond
(4) maximum diameter of fiber and (if possible) probe, 0.5 millimeter

This Phase I feasibility study considered several important technical OBJECTIVES, listed below.

(1) Conceptual Design of Measurement System:

(a) Select an optimum design concept for monitoring pressure induced variations in a Fabry-Perot etalon.
(b) Devise a method of isolating pressure changes from temperature changes.
(c) Find the laser power and the spectral range of the etalon required to meet the program goals.
(d) Predict the range and resolution of the etalon pressure sensor. Determine if the proposed system is feasible for meeting the specifications above.

(2) Demonstrate Key Components:

(a) Select an etalon material, and experimentally calibrate the etalon's pressure and temperature response.
(b) Choose the stable laser source, and experimentally demonstrate how to operate or modulate it for the detection concept chosen.

(3) Determine How to couple System Elements:

(a) Demonstrate that the laser, etalon, and detector can be efficiently coupled to optical fibers without reflections destabilizing the laser.
(b) Verify that the fiber is not subject to effects that will degrade the pressure measurement such as stress induced birefringence or strain induced misalignments.

* 14 pounds per square inch pressure (psi) is approximately 1 atmosphere equating approximately 100 kilo-Pascals.

Results

The results of the Phase I research are stated below by task.

Task 1: Design measurement system for desired range and resolution.

a) A detection system for pressure measurement was selected. A birefringent etalon system was chosen because of its simplicity and ability to use just one fiber to deliver light both into and out of the actual pressure sensor. The optical thickness (index of refraction times the actual thickness) is different for the two polarizations that fall on the etalon. The thickness of the etalon decreases with increasing pressure, thus changing the optical thicknesses. Therefore the intensity of reflected signal at a specific pressure is different for the two polarizations. With just one reflected signal, the only information available is that a pressure change is occuring. With two different reflected signals (Figure 1), effectively two etalons, the magnitude and the direction of changes can be determined. A system concept diagram is shown in Figure 2.

Other system concepts were considered for use in pressure measurement, but were rejected for various reasons. One idea was to use a diode array to monitor pressure-induced variations in etalon transmission. By watching etalon fringes the pressure history of the etalon could be recorded because increasing pressure would decrease the effective optical thickness of the etalon, and the bull's eye fringe pattern would diverge. The disadvantages of this approach were the cost of a diode array and the need for many optical fibers to convey light to and from the etalon sensor head. This would have increased the necessary cable and sensor diameters, and would have been difficult to align. Another approach that was considered involved the use of only one fiber for both source laser illumination of the etalon and detection of the reflected signal. The wavelength of the laser would be modulated in order to resolve ambiguity in which direction pressure was changing when changes in the etalon reflectivity were observed. Instead of gaining information from the variation in etalon reflectivity with angle, the fringe pattern, the same information could have been gained from the variation of reflectivity with wavelength. Although this approach was attractive, the use of a voltage-driven piezoelectric pressure transducer on the laser source made this method more complex than was necessary.

b) The sensor is pressure and temperature dependent. However, temperature effects occur at a much slower rate than pressure changes. It has been calculated that a 1 degree C change in temperature is equivalent to a 1000 psi change in pressure. The thermal effects of the etalon can be ignored, even with temperature jumps of 1000 degrees C, over the specified program goal of a 0.1 ms temporal response for a sensor that is surrounded by a 2 mm thermal isolation cap. This cap, Figure 3, will be made out of the same material as the etalon. A full pressure response at the sensor occurs in less than 1 microsecond, while only a 0.1% thermal response takes 10 ms. The etalon diameter was determined by the measurement time required. Unfortunately, the specifications of 0.5 mm sensor cannot be met due to the thermal isolation cap around the sensor area. However, if the temperature is stable to within about

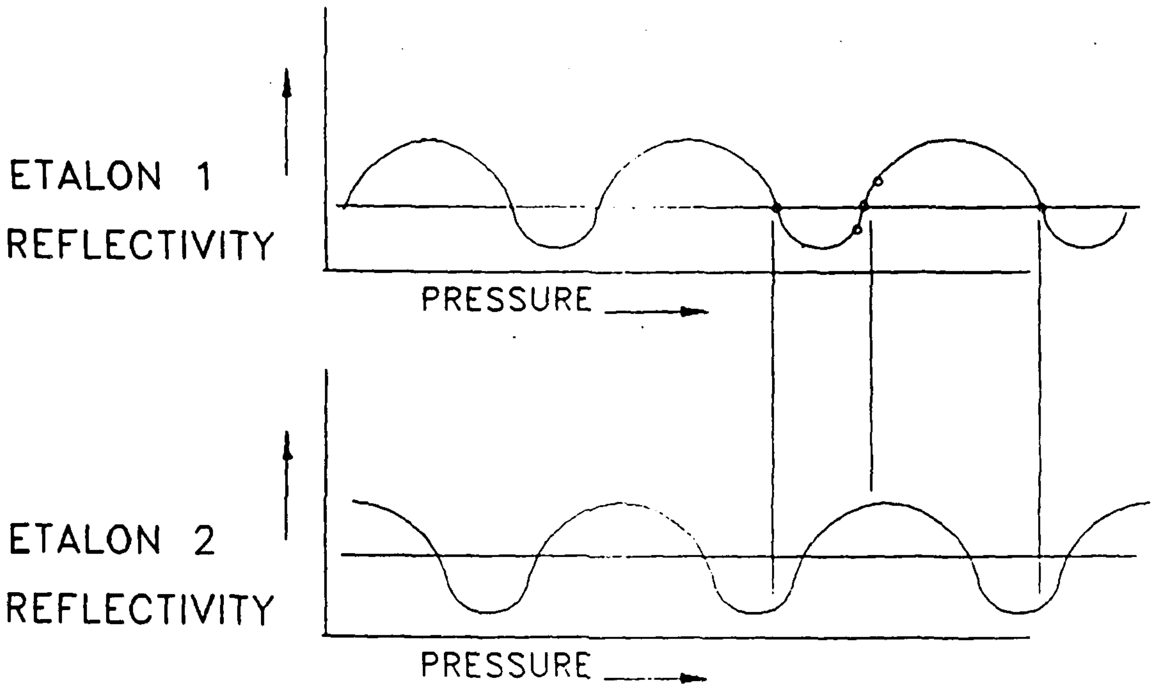

Figure 1. Two signals are needed to determine both the magnitude of the pressure change and the direction. With the two signals out of phase, all the information is obtained merely by counting the number of zero crossings for one polarization and noting the sign of the reflected signal for the other polarization.

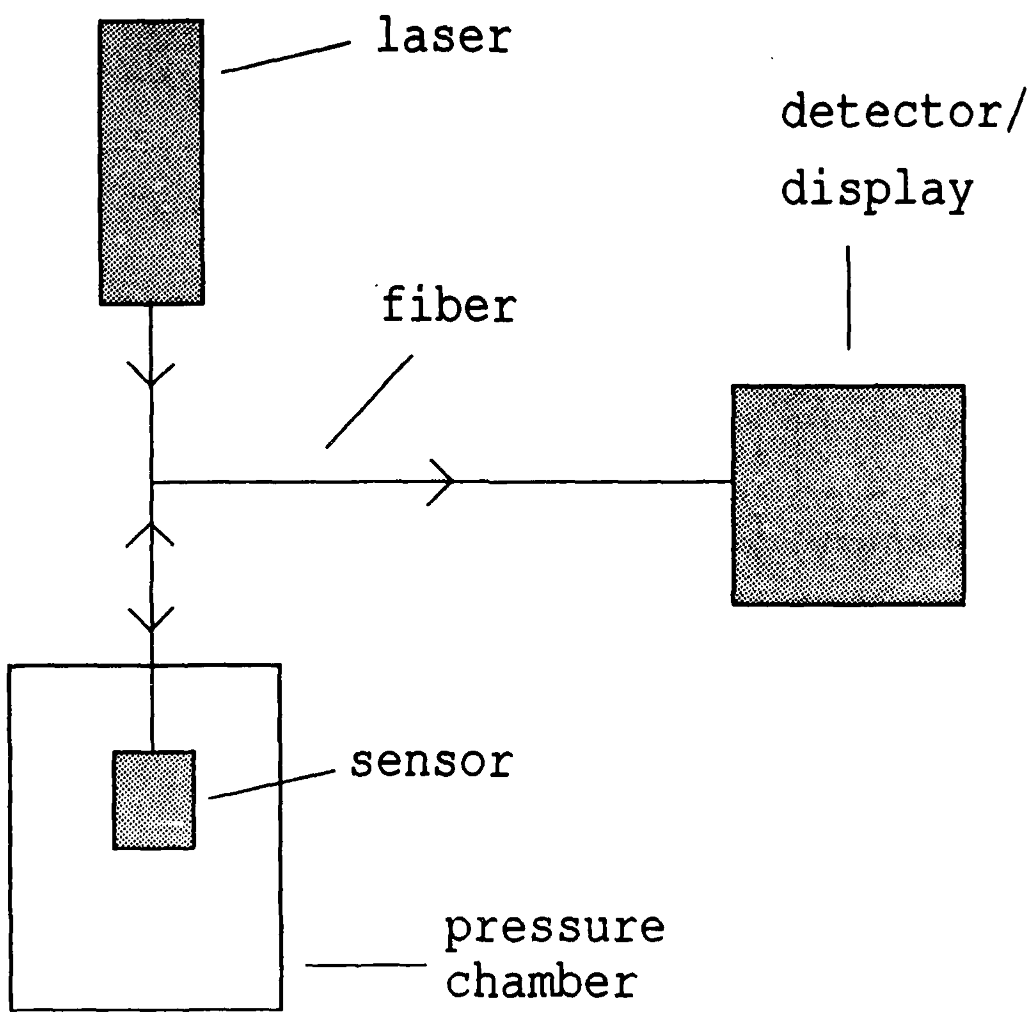

Figure 2. A diagram of the pressure measurement system concept is shown. A laser source is coupled into an optical fiber which transmits the light into a pressure chamber. The light is reflected from the pressure sensor and returns through the same fiber. Part of the return signal is split off and transmitted through more fiber to a detector where the data is output.

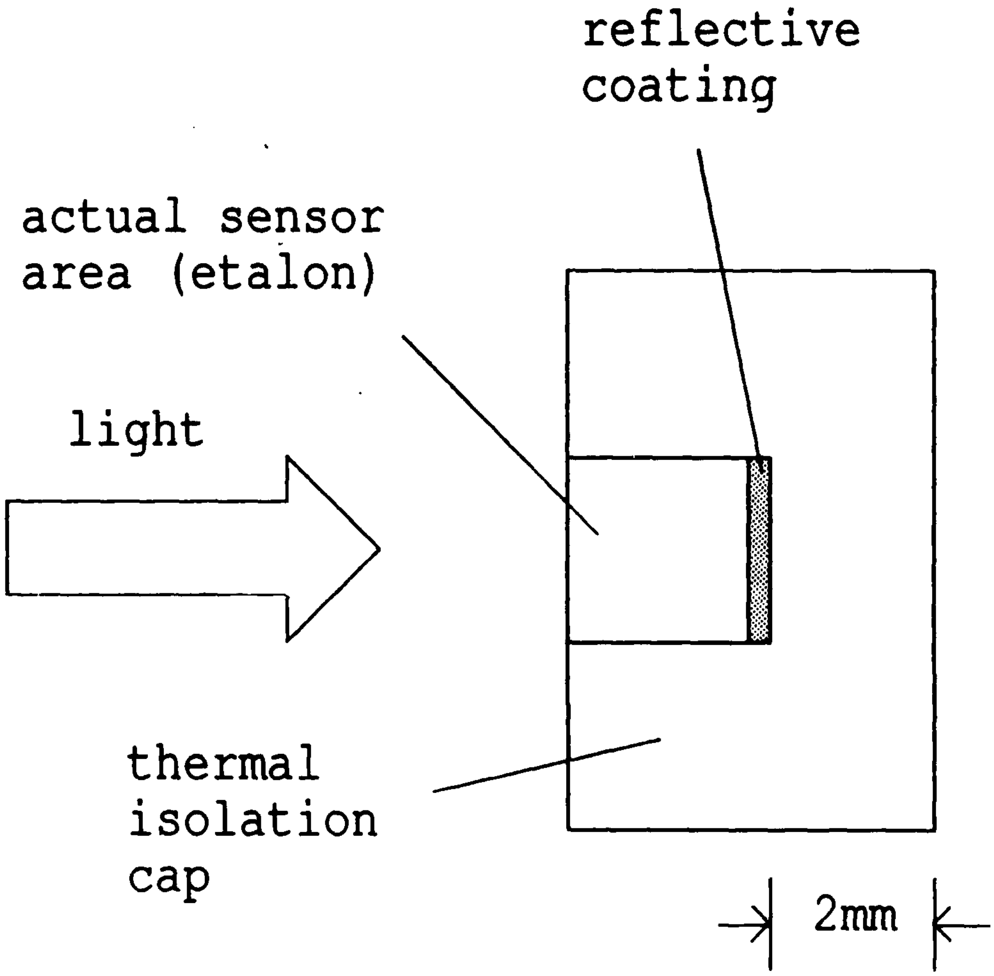

Figure 3. A diagram of the etalon with a thermal isolation cap, a 2 millimeter thick layer of sapphire. A full pressure response occurs in less than 1 microsecond, whereas only 0.1% of the pressure response will take 10 milliseconds. The etalon diameter, D, is determined by the measurement time required, t: $D \propto t^2$

10 degrees C during the 10 millisecond test, a 0.5 millimeter sensor may be possible.

c) A laser power of 4 mW was adequate for the tests performed under the program goals. The return signal from the etalon, after the losses from the various optical components of the system, was on the order of 0.05 mW which was sufficient for detection and analysis.

d) The range of the etalon pressure sensor is 0 - 150,000 psi with a resolution of about 5000 psi. The maximum pressure will be set by component survival. The resolution is dependent on the thickness of the etalon. As the etalon is subject to pressure changes, the reflected signal passes through alternating bright and dark fringes. For a 5 mm thick etalon, each fringe is equivalent to a 3000 psi pressure change.

Task 2: Demonstrate key components.

a) An etalon material was selected to meet the needs of mechanical hardness, optical quality, chemical inertness, and birefringence. Sapphire was the optimum choice. Quartz was less expensive to fabricate, but the optical activity of quartz gave a signal that was too complex to use for pressure measurement. Optical activity causes a rotation in transmitted polarization. The amount of rotation was highly sensitive to the angle of the incident light. This rotation, along with the birefringent properties of quartz, made it difficult to analyze the reflected signals.

Experimentally testing etalon coatings was unnecessary since the coating would not be exposed to the possibly harsh environment of the pressure chamber. This is because the etalon coatings will contact the Selfoc lens on one side and the sapphire cap on the other. When the problem of thermal isolation was solved by designing a thermal isolation cap of the same etalon material, the problem of finding a durable, rugged coating was eliminated as well.

The tested optical fiber is a single-mode quartz fiber for 1059 nm light, with 0.9 dB/km attenuation. It has a core diameter of about 6 microns, a glass sheath diameter of about 125 microns, and a plastic jacket diameter of about 250 microns. The fiber was optically glued to a Selfoc lens. Each end of the fiber was stripped of its plastic jacket and inserted and glued into a glass capillary tube. The end of the fiber and capillary tube were then polished together with optical lapping film to an optical smoothness. This gave a wider surface (3.8 millimeters) onto which the Selfoc lens could be attached. Index-matching, UV curing optical cement was tested successfully for bonding this Selfoc lens and the fiber.

b) The MISER (Figures 4a and 4b) laser-diode pumped Nd:YAG laser source manufactured at Lightwave Electronics Corporation was chosen for its wavelength stability, its compatibility to optical fibers (wavelength and single transverse mode), and cost effectiveness. The amplitude jitter is less than 0.5%, ideal for a measurement where small fluctuations in detected signal are critical. The complete experimental schematic is shown in Figure 5.

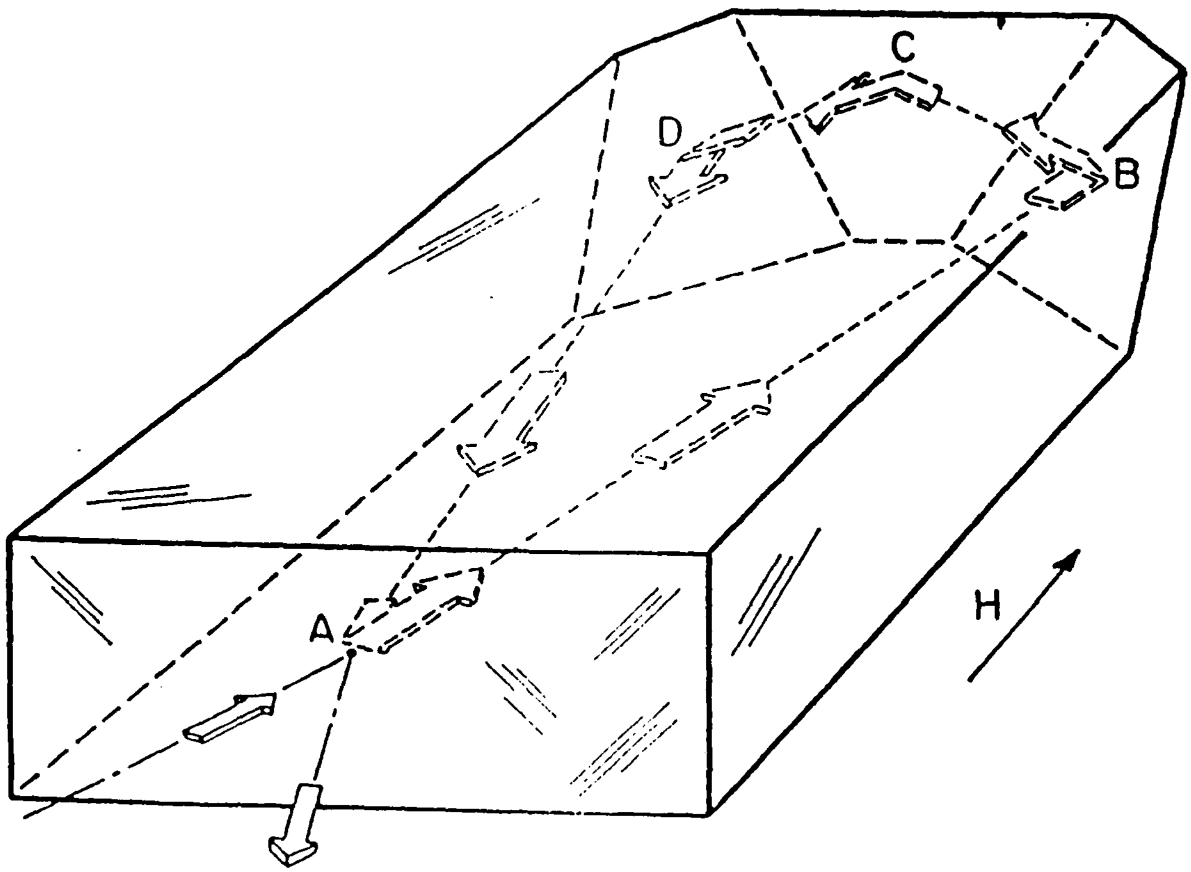

Figure 4a. (From Kane & Byer [4]) The Monolithic Isolated Single-mode End-pumped Ring (MISER) laser shown here is an ultrastable laser source suitable for use in pressure sensing. This laser as built at Lightwave Electronics is fabricated in a Nd:YAG crystal which is only about 5 mm long. The MISER laser is pumped by a laser-diode (not shown) focused through the crystal at point A, and the output beam emerges from the same point. A magnetic field, H, is applied to establish unidirectional operation.

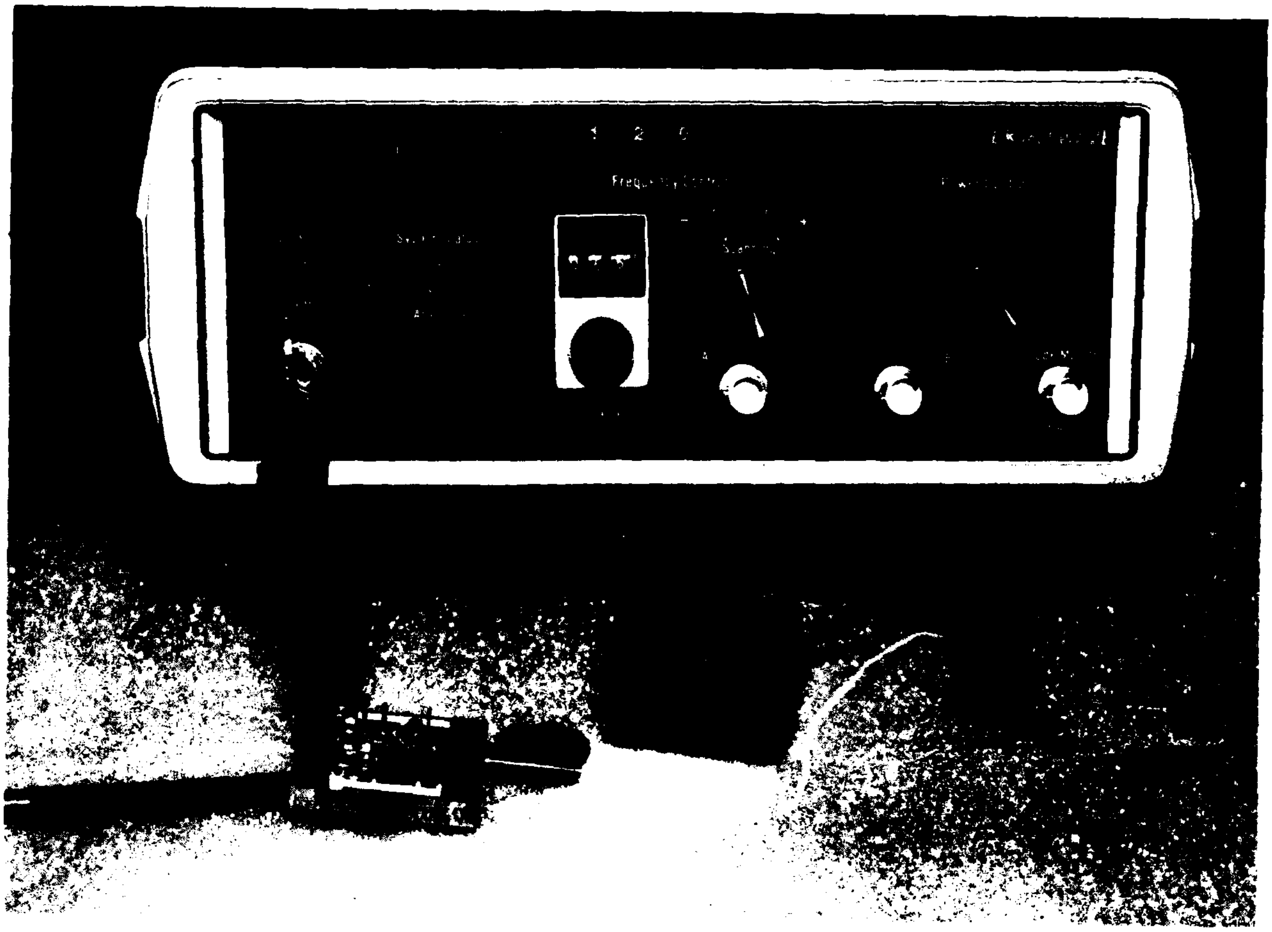

Figure 4b. A photograph of the MISER laser source (with the cover off) and power supply is shown.

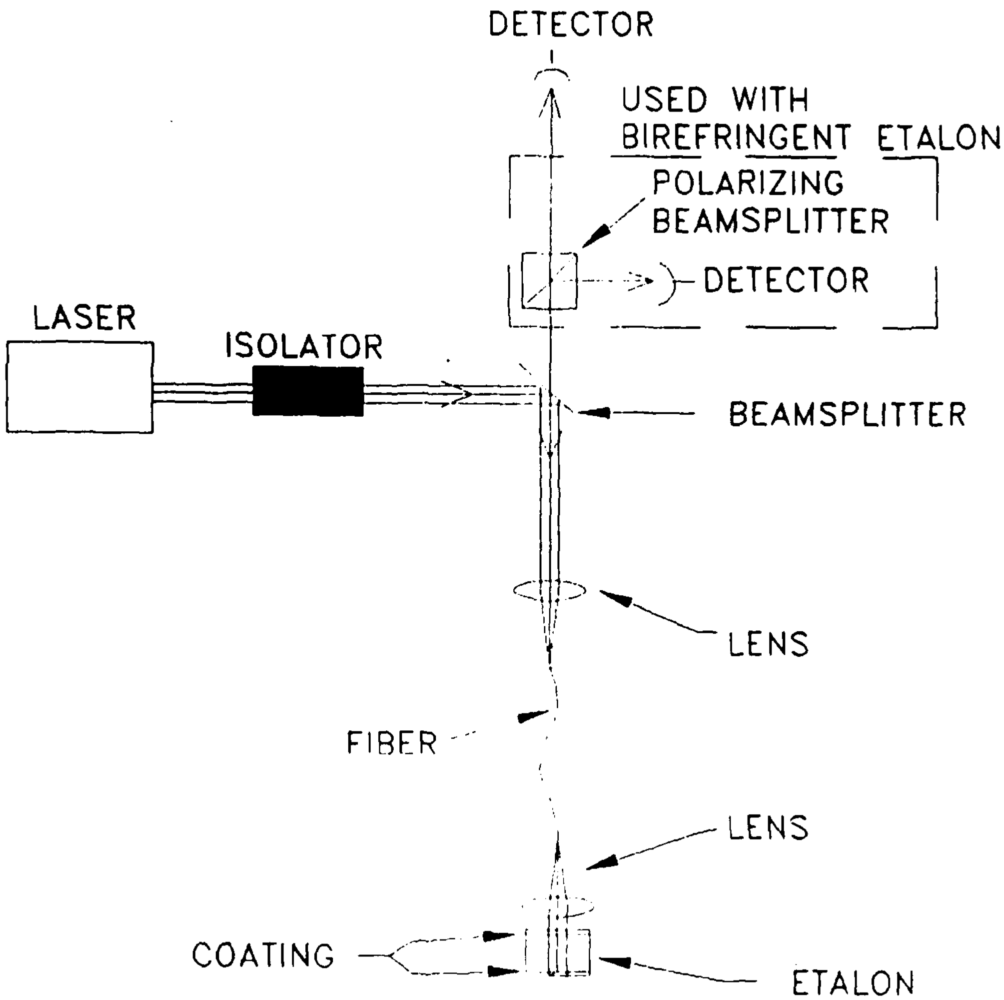

Figure 5. Shown above is a schematic for the complete experimental set-up.

Task 3: Determine how to couple system elements.

a) A key concern of this research was coupling the laser to the sensor with a fiber without unwanted feedback. The coupling efficiency of the laser into and through the optical fiber was found to be about 80%. An achromatic lens triplet was used to focus the light into the fiber. In order to minimize detector size and to help in alignment preservation, the system previously mentioned in which the fiber and lens were glued together was designed. The coupling efficiency through a fiber and a Selfoc lens mounted directly on the end of the fiber was over 50%.

Before maximum coupling levels could be reached, reflections from the etalon and the cleaved ends of the fiber destabilized the laser. This feedback sensitivity necessitated the use of a Faraday isolator. The isolator transmitted about 60% of the light from the MISER but rejected over 99.9% of the reflected light from returning to the laser. This kept the miser from breaking into feedback-induced oscillations.

b) Another difficulty which was noticed during the tests was the temperature sensitivity of the fiber itself. Due to the coherence length of the laser (50 km), the fiber behaved like a long etalon. The length of this etalon would change with variations in temperature, even those as slight as from a hand held a centimeter beside the fiber, and so the amount of transmitted light would also fluctuate. To eliminate this problem, the front surface of the fiber needed to be angled or anti-reflection coated. It was impractical to AR coat one end of an optical fiber since it was often necessary to recleave the fiber during an experiment. It was also difficult to cleave the end of a fiber at an angle and maintain a good quality surface. A temporary solution was devised in which a microscope slide cover glass was optically glued onto the front surface of the fiber at an approximately 10 degree angle, shown in Figure 6. The index-matching cement filled the gaps between the fiber end and the angled cover glass, so the cover glass acted as the front surface of the optical fiber. This was sufficient for a feasibility study, but to increase coupling efficiency in future work, one surface of the front Selfoc lens should be angled and anti-reflection coated, diagrammed in Figure 7. The experiments also verified that the fiber was not subject to stress induced birefringence or misalignments. Polarization was preserved for the lengths of fiber used in these tests (2 - 3 meters), even with bends in the fiber of up to 90 degrees.

c) Since pressure changes from 0 - 150,000 psi were not practical in our laboratory setting, equivalent temperature changes were used. The etalon, Figure 8, was heated from room temperature to over 150 degrees C, and the passing of the etalon fringes for the two polarizations was recorded on a stripchart recorder. A typical data run is shown in Figure 9. With 125 degrees C of heating, about 42 fringes passed, as expected. Variations in the phase difference of the two polarizations were noted for variations in the angle of the etalon with respect to the optical axis. The clearest (easiest to analyze) results were obtained with the etalon tilted at 3 degrees to the optical axis. This gave a phase difference between the two polarizations of 65 degrees. A photograph of the complete experimental set-up is shown in Figure 10. This experiment was made without fiber coupling to the etalon, because the reflected signal was not colinear with the incident laser beam. The tilt in the etalon, and thus the crystal axis, was necessary in order to keep the phase difference from being as high as 180 degrees. The benefit of having the "two" etalons is lost at this phase difference. If the etalon was cut so that the crystal axis was not perpendicular to the surfaces of the etalon, then an optical fiber could be used for both the original and return signals.

Figure 6. A microscope objective (left) focuses light into an optical fiber (on top of the rectangular block on the right). A thin cover glass (attached on the left side of the block) is UV glued to the front surface of the fiber at an angle. This eliminated the temperature sensitivity of the fiber.

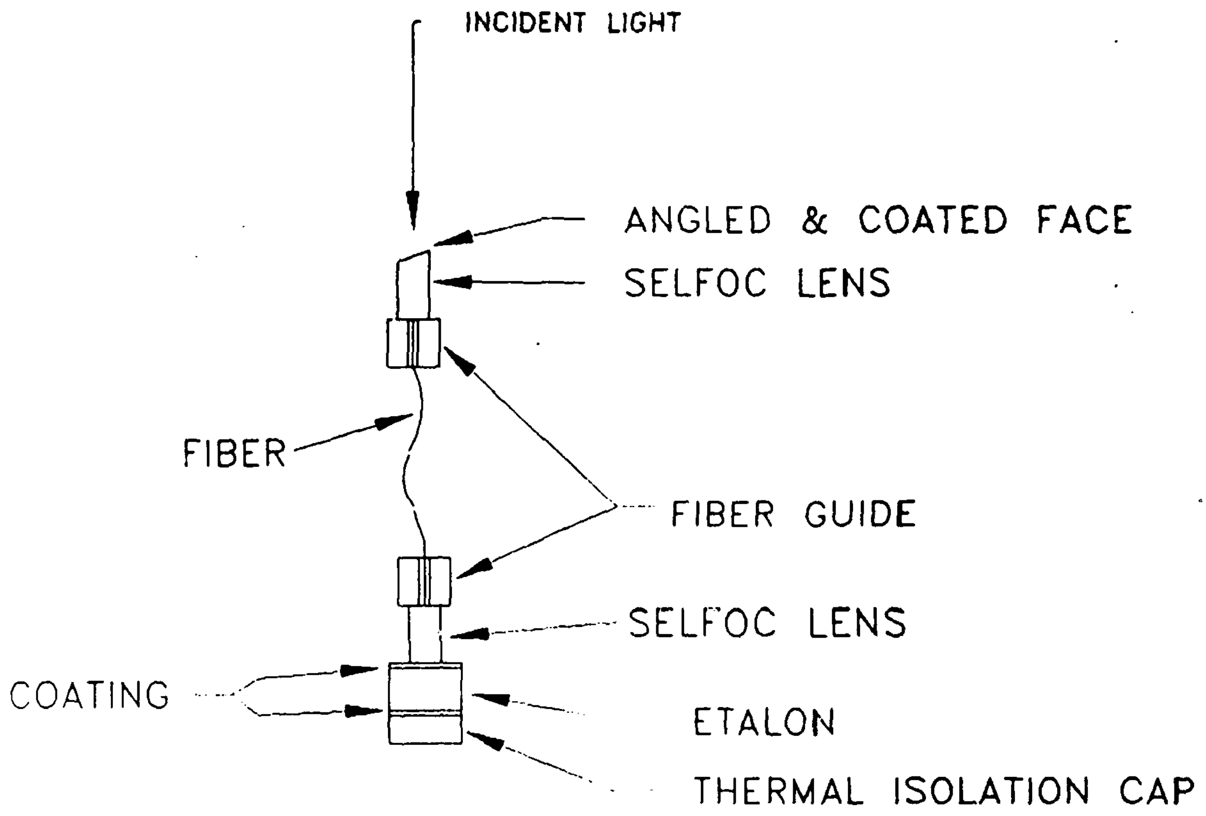

Figure 7. A more durable solution to the problem of the fiber acting like an etalon is shown. The front surface of the focusing Selfoc lens is angled and anti-reflection coated. The only reflective surfaces are the two coated etalon surfaces.

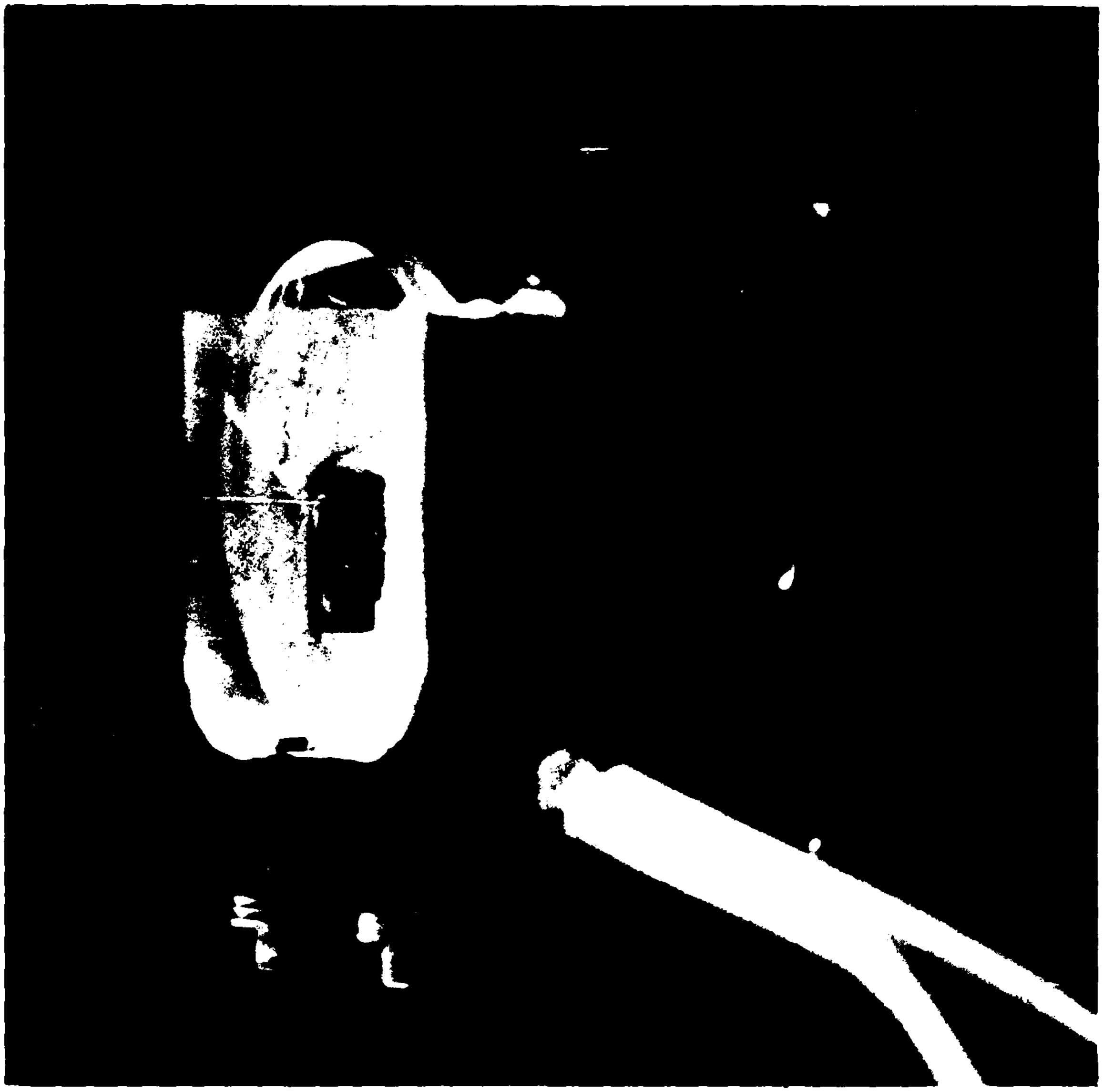

Figure 8. A photograph of the birefringent etalon is shown. The etalon is held in a mount that allows heating.

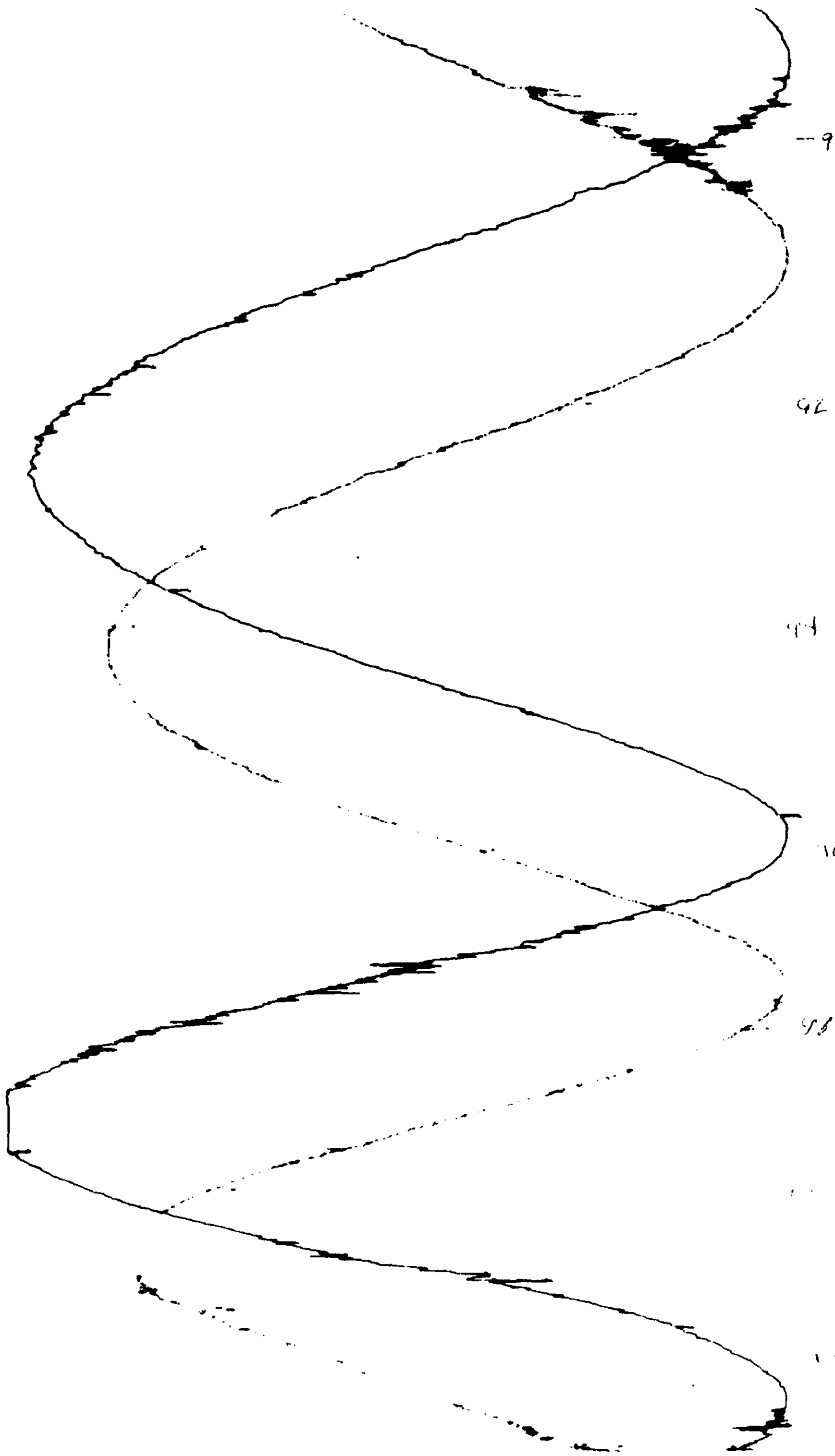

Figure 9. A typical stripchart recording of the variation in reflectivity with temperature is shown. The two traces are the signals from the two different polarizations, out of phase by 65 degrees. Each peak is a temperature change of about 3 degrees C, equivalent to about a 3000 psi pressure change.

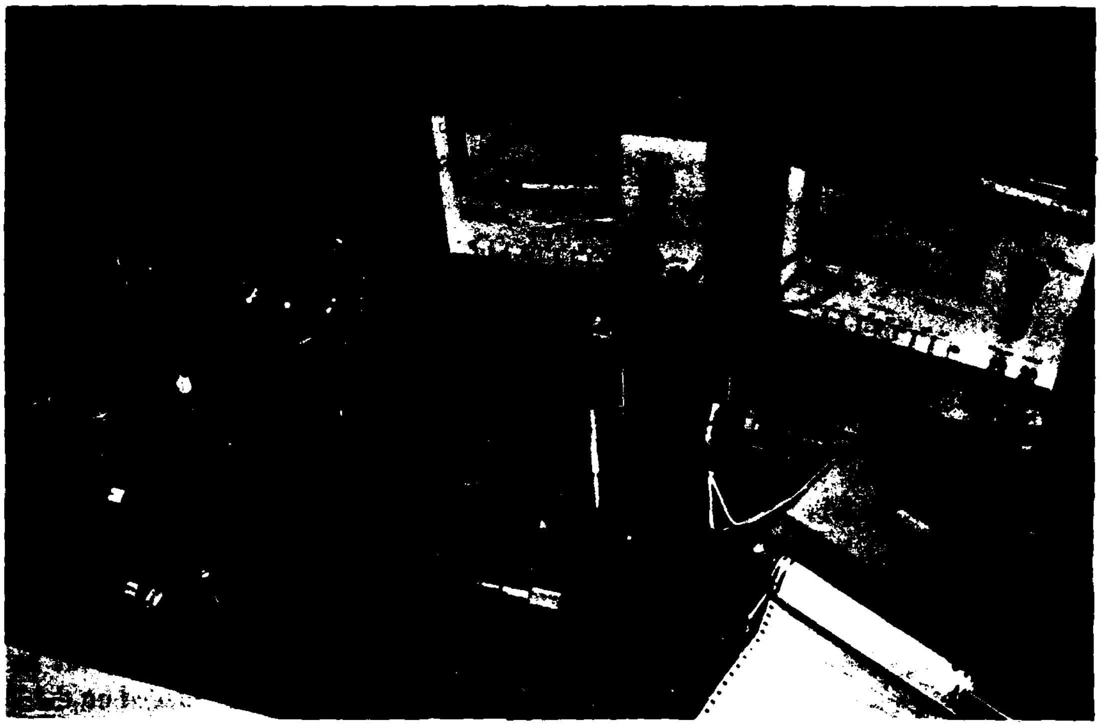

Figure 10. A photograph of the experimental set-up is shown. From left to right are: the MISER laser, collimating lens, Faraday isolator, beam expanding lenses, beamsplitter, and heated etalon. Above the beamsplitter can be seen the polarizing beamsplitter cube, and two photodiodes. At the back of the optical bench is the power supply to the MISER and the two power meters for the photodiodes. At the bottom right of the photo is the dual input stripchart recorder.

Design Aspects of an Interferometric High-Pressure Sensor

In order to assemble a bench-top pressure measurement system that could be tested inside a pressure chamber, several main components are needed. The MISER as a laser source has already been tested successfully. A Faraday isolator is needed to minimize feedback to the laser, and is also manufactured at Lightwave Electronics. These isolators, when properly aligned, have throughputs of 70% and isolation of 100,000:1. For maximum isolation, they need to be temperature controlled. The electronics are already available at Lightwave to do this.

The positioning of the Faraday isolator is critical. In order to facilitate this, a tilt stage and an X-Y-Z translation stage are required. Another X-Y-Z translation stage is needed for the positioning of the optical fiber assembly. Good coupling efficiency requires precise positioning of the fiber to center the core in the focused laser beam. Due to the extremely small diameter of the fiber's core (6 microns), submicron positioning resolution is desirable. This positioner will also be useful in the initial alignment and attachment of the Selfoc lens to the fiber end (surrounded by the capillary tube).

Optical mounts are also needed to support the etalon and attached fiber and lens assembly. The same care is needed when aligning and epoxying these components together as on the input end of the fiber, and so micropositioners are again useful. Once the components are attached, however, the only positioning requirement is that minimum stress be placed on the assembly to keep the fiber from getting stretched.

Two detectors are needed for the two polarizations of light returning from the etalon. These detectors must be able to sense microwatt levels of light and have time responses better than the 0.1 millisecond response specified for the pressure measurement system. An analog output is desirable to record the data on a stripchart recorder.

The next steps in this program include testing a bench-top system under varying pressure, and building a rugged prototype pressure detector for a performance test at a user site.

Recommendations for Phase II Development

a) Additional Work Required

The logical next step in the testing of this pressure measurement device is to perform bench-top pressure chamber tests. The performance and results should be similar to those achieved under variations in temperature, but actual pressure variations should be checked in order to calibrate the sensor. Also, compatibility with the test chamber needs to be verified. The signal-to-noise levels need to be examined.

When the results appear satisfactory, the components should then be refined for the construction of a prototype pressure measurement instrument. At this point, not only will the lenses, fiber, and etalon be cemented together, but the laser should be fiber coupled directly to the Faraday isolator with Selfoc lenses. This would reduce the possibility of misalignment under test conditions. A customized etalon cut to fit into a standard pressure gauge package would allow easy installation of the sensor. The data analysis electronics and software would be added at this point. Instead of analog detector outputs recorded on stripchart, digital computer interfacing would allow easy data analysis and storage. Software that could recognize the number of zero crossings and sign of the reflected signals and translate this data into actual pressure values would give quick, easily accessible pressure versus time information.

A detailed estimate of the cost to develop such a product will be given in the Phase II proposal. The cost of manufacturing a final product in small quantities is dominated by the laser source and the data handling/display electronics. Both the laser source (including a MISER, Faraday isolator, and necessary optics), and the electronics would cost on the order of $10,000 each, while the sensor (including the fiber and other optics) would cost around $1,000. The cost to replace the sensor head would be around $500. The total cost, estimated here at $21,000, would undoubtedly be much less for higher volumes.

b) Conclusions

The results of this Phase I study have proven the feasibility of an optical pressure measurement system, and have provided an understanding of the performance and cost of the system. Efficient coupling of the key components has been shown, demonstrating that an optical pressure transducer can be made that has the properties of compactness, wide pressure range, immunity to electro-magnetic interference, and low cost. The next steps in this program include testing a bench-top system under varying pressure, and building a rugged prototype pressure detector for a performance test at a user site.

Relation to Future Work

a) Government Applications

The successful Phase I research provides a base from which a pressure sensor can be developed. This product will make it possible to measure pressures in applications where previously existing measurement systems had insufficient life, range, compactness, or durability.

In addition to high pressure measurements, temperature measurements will be possible as well with interferometric methods. The response of the reflectivity of the etalon to temperature has already been demonstrated. This could be calibrated for accurate thermal measurements in harsh environments.

b) Commercial Applications

The research completed in Phase I is useful for not only a potential pressure sensing product, but for the information gathered on fiber coupling. Fiber coupling of 1.32 micron MISER lasers is essential for communication applications, where 1.32 micron laser transmission through single-mode fibers allows both maximum data transference rates and distances between amplifiers. Also, the rapidly expanding applications of optical fibers as interferometric sensors requires the use of lasers with extreme coherence lengths, such as the MISER.

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